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THE FEDERAL
R&D PLAN FOR AIR-POLLUTION CONTROL BY COMBUSTION-PROCESS MODIFICATION

Final Report
prepared under Contract CPA 22-69-147

January 11, 1971

for
Air Pollution Control Office
ENVIRONMENTAL PROTECTION AGENCY

BATTELLE MEMORIAL INSTITUTE
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Contract CPA 22-69-147

to

Air Pollution Control Office
ENVIRONMENTAL PROTECTION AGENCY

January 11, 1971

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ABSTRACT

This report presents the results of a study conducted by a team at Battelle-Columbus for the Air Pollution Control Office to (1) identify gaps in combustion technology, particularly in the understanding of how combustion processes may be modified to reduce pollutant emissions, and (2) recommend a comprehensive 5-Year Plan with priorities for effectively allocating resources for APCO-supported combustion R&D directed toward meeting projected needs for air-pollution control of energy-conversion systems by combustion modification. The resulting Plan includes only R&D for modification of the combustion process, and does not include downstream control systems, as they are covered in other APCO plans.

Combustion applications considered as elements of the Plan include: central-station power generation; industrial processing; industrial steam generation, commercial and residential heating; gas turbines and external-combustion engines; and reciprocating internal-combustion engines. Also considered are needs for supporting fundamental research.

A 5-Year Plan of combustion R&D is presented, with "R&D opportunities" identified and ranked in five priority levels. The Plan includes the description of 49 applied R&D opportunities in specific combustion application areas and 27 research opportunities of a more fundamental and broadly applicable nature. Applied-R&D opportunities were ranked by a priority rationale which includes the following factors as criteria: (1) pollutants affected, (2) likely percentage reduction of nationwide combustion emissions by completing and implementing the specific R&D, (3) time to implementation of R&D results, (4) likelihood of emission reduction by some noncombustion or downstream control method, and (5) relative implementation cost. Fundamental research opportunities were ranked by a different priority rationale based on their relevance to applied-R&D needs.

The methodology for priority ranking, both within and across different application areas, can be used to update the Plan periodically as new technology and criteria emerge.

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Members of the Battelle study team are identified as authors of individual chapters; however, contributions of other staff are acknowledged, especially the editorial guidance of Dolores M. Landreman.

THE FEDERAL
R&D PLAN FOR AIR-POLLUTION CONTROL
BY COMBUSTION-PROCESS MODIFICATION

Final Report
Contract CPA 22-69-147

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THE FEDERAL R&D PLAN FOR AIR-POLLUTION CONTROL BY COMBUSTION-PROCESS MODIFICATION

Chapter I

EXECUTIVE SUMMARY

David W. Locklin
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BACKGROUND

Historically, the thrust of most R&D in the combustion field has been to optimize equipment performance characteristics rather than to reduce pollutant emissions. For example, burner or engine development has usually been conducted with the objective of enhancing operating range, response, efficiency, reliability, manufacturing economy, or compactness. While the limitation of smoke emission has traditionally provided one performance constraint for the designer, only comparatively recently has R&D attention been given to the relation of combustion processes and system design to emissions of other pollutants.

Thus, only a small portion of past combustion research is directly applicable to air-pollution considerations, but much more is indirectly relevant because of its potential contribution to the overall understanding of the combustion process. This study has utilized generally pertinent combustion technology, as background, in addition to specific results of R&D aimed directly at air-pollution control.

SCOPE OF R&D PLAN

The 5-Year Combustion R&D Plan recommended in this report is directed to the control of pollutant emissions from stationary and vehicular combustion sources through modification of combustion processes, rather than emission control by add-on or downstream devices. The Plan is confined to combustion R&D, both fundamental and applied, for energy-conversion systems utilizing prime fuels and air.

The limitations imposed by this scope can be emphasized by the following tabulation:

Within Scope of Plan	Outside Scope of Plan
• Combustion carried out for the purpose of energy conversion, including the production of heat, as the prime objective.	• Combustion for other purposes, such as incineration, chemical processing, etc.
• Pollutant control gained by modification of the combustion process.	• Downstream controls, even though combustion may be involved; limestone reactions in furnaces or fluidized beds.
• Combustion processes using prime fuels (i.e., those normally sold commercially).	• Combustion processes using waste fuels, by-product fuels, specialty fuels, etc., even though carried out for energy conversion purposes.
• Fundamental research needed for understanding of combustion processes and their effects on pollutant emissions.	• Associated research in other technical areas, even though necessary to apply the results of combustion research, such as alloy development, heat transfer equipment, etc.

THE FEDERAL R&D PLAN FOR AIR-POLLUTION CONTROL BY COMBUSTION-PROCESS MODIFICATION

to
Air Pollution Control Office
ENVIRONMENTAL PROTECTION AGENCY

CHAPTER I

EXECUTIVE SUMMARY

Combustion processes for energy-conversion purposes constitute the major source of air pollution in the United States. Thus, effective planning of R&D in this area is of key importance for the long-range success of the nation's air-pollution-control program. Recognizing this need, the Air Pollution Control Office initiated this in-depth study to (1) identify gaps in combustion technology, particularly in the understanding of how combustion processes may be modified to reduce pollutant emissions, and (2) develop a comprehensive 5-Year Plan for effectively allocating resources available for APCO-supported combustion R&D directed to meeting projected needs for air-pollution control.

Figure I-1 illustrates the relative magnitude of the problem to which this Plan is directed by showing the percentage contribution of energy-conversion combustion processes to the nationwide problem arising from emissions of various pollutants from all sources. (These emission data are further discussed in Chapter II.)

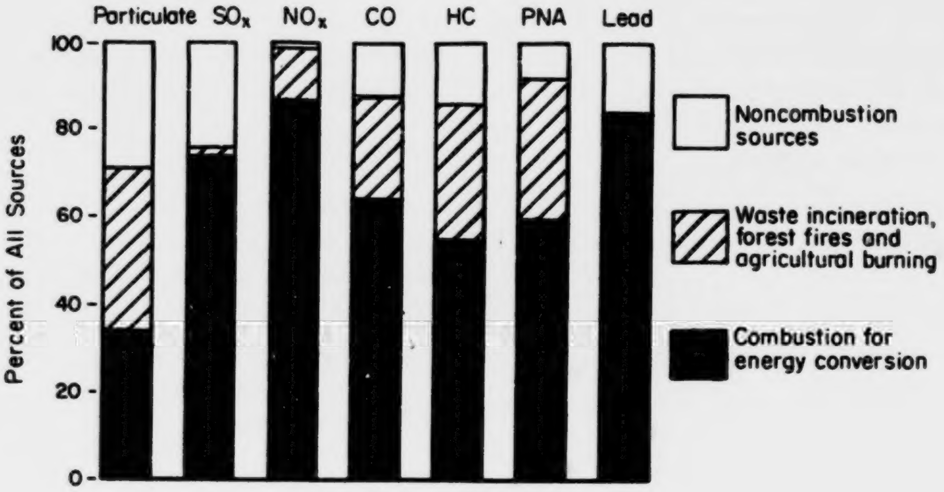

Figure I-1. Percentage Contribution of Combustion-Source Emissions to the Total Nationwide Inventory of Pollutant Emissions

ORGANIZATION OF THE 5-YEAR R&D PLAN

The recommended R&D Plan is organized by program elements, identified by application areas or categories of major pollutant sources rather than by pollutants. Consequently, combustion R&D opportunities for like applications are grouped together in separate program elements (e.g., power plants, IC engines, etc.); all relevant pollutants are considered within each element. Supporting fundamental research constitutes an additional program element.

ORGANIZATION MATRIX

The matrix chart shown in Table I-1 illustrates the manner in which the Plan is organized in terms of the program elements and the pollutants considered. The numbers in the chart give the percentage contribution of each source category to the total emission of a particular pollutant from all combustion sources within the scope of the Plan. Thus, these numbers serve to identify those sources that are major emitters of a specific pollutant and define the importance of controlling a specific source.

Table I-1. Organization Matrix for Combustion R&D Plan

[illegible]	APPLIED R&D FOR COMBUSTION SOURCES					SUPPORTING FUNDAMENTAL RESEARCH
	Continuous-Combustion Sources				Cyclic Comb.	
Pollutants	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] Ch. VII	[illegible] Ch. VIII
1. Products of Incomplete Combustion						
Combustible particulate	☐ 18	☐ 6	▤ 45	☐ 1	▤ 30	▩
CO	<1	☐ <1	☐ 1	☐ 1	▩ 98	▩
Gaseous HC	<1	<1	☐ 1	☐ 1	▩ 98	▩
Polynuclear aromatics	<1	☐ 4	☐ 90	n	☐ 6	▩
Odor	–	–	☐ –	▤ –	▤ –	▩
2. Oxides of Nitrogen, NO$_x$	▩ 21	▤ 3	▤ 17	▩ 1	▩ 58	▩
3. Emissions Resulting From Combustion-Improving Additives						
Lead and other trace metals	n	n	☐ n	☐ n	▤ 99	☐
4. Emissions Resulting From Fuel Contaminants						
Sulfur, SO$_x$	▤ 63	☐ 5	☐ 31	n	1	☐
Ash	☐ 72	☐ 3	☐ 25	<1	<1	☐
Other noncombustible additives	–	–	–	–	–	☐

Potential Impact of Combustion R&D: ▩ Highest ▤ Medium ☐ Lowest

Numbers in table refer to percentage contribution from each class of source to the total emission of the identified pollutant from all combustion for energy conversion (1966 data); n indicates negligible.

The shaded boxes in Table I-1 indicate the degree to which combustion R&D within the particular program element is expected to contribute to the overall control of the specific pollutant emission from energy conversion combustion sources. Factors considered in setting the degree of potential impact of combustion R&D are:

1. The extent to which a specific pollutant may be amenable to control by modification of the combustion process
2. The contribution of the source to the total combustion-derived emission of a specific pollutant, as indicated by the percentages shown
3. The judgment of the project team as to the importance of the specific source and pollutant, either at the present time or in the future.

Thus, while SO_X is high on the list of pollutants under attack by control authorities, it is not readily controllable by combustion modification only. Gas turbines and external-combustion engines are not presently strong contributors to the nationwide NO_X level; however, the new interest anticipated in unconventional automotive engines places this area in a high-potential-impact category. Where no box is shown, the combination of pollutant and source was considered outside the scope of the R&D Plan or of minor significance.

The program elements of the Plan and the pollutants considered are categorized in the following manner.

Applied R&D for Combustion Sources

For convenience in treating the applied technology and pertinent R&D needs, combustion sources were divided into two main classifications: *continuous-combustion systems* and *cyclic-combustion systems.* These classifications include the following combustion applications, or pollutant sources:

Continuous-Combustion Systems

- Central-Station Power Plants
- Industrial Processing
  (combustion for thermal processing, excluding steam generation)
- Industrial Steam Generation and Commercial and Residential Heating
  (including boilers not covered under central stations)
- Continuous-Combustion Engines –
  Gas Turbines and External-Combustion Engines

Cyclic-Combustion Systems

- Reciprocating Internal-Combustion Engines.

These individual source categories are considered as program elements within the Plan.

Supporting Fundamental Research

A sixth program element is comprised of fundamental and broadly applicable research that will support applied-R&D needs. This element covers fundamental physical and chemical aspects of combustion processes having relevance to applied-R&D opportunities in one or more of the source categories. It is anticipated that funding of fundamental research in this program element will be through the grants mechanism, while the applied R&D is more likely to be funded through the contracts mechanism or to be conducted as in-house programs.

Classification of Pollutants

Pollutants of primary interest were classified according to the manner in which, or the degree to which, combustion modification offers a means of control and, thus, where combustion R&D can be effective. Four main categories were defined:

1. Products of Incomplete Combustion

When considering emissions from the combustion process itself, it was convenient to group pollutants that are products of incomplete combustion and, thus, can be strongly influenced by conditions that are amenable to control through combustion-system design. These pollutants are: combustible particulate, CO, gaseous hydrocarbons, polynuclear aromatics, and odor. R&D directed to modification of the combustion process can be particularly effective in the control of pollutants in this category.

2. Oxides of Nitrogen

The formation of NO_x is strongly influenced by the time-temperature pattern in the combustion process. The relations of time, temperature, and concentrations which are important to NO_x formation can be controlled to some extent in combustion-system design and, thus, modification of the combustion process offers promise as a means for NO_x control.

3. Emissions Resulting from Combustion-Improving Additives

Another category of combustion pollutants includes those resulting from combustion-improving additives, principally lead as an antiknock agent in gasoline. Here the principal R&D interest is in engines, fuels, or combustion conditions that eliminate the need for combustion-improving additives. Combustion-improving additives have not had widespread application for continuous-combustion systems. Additives used for other, noncombustion purposes are considered in the fourth category.

4. Emissions Resulting from Fuel Contaminants

Contaminants that are present naturally in fuels and noncombustible additives are the origin of still another category of pollutants. These contaminants include sulfur compounds, ash, and additives for stability or corrosion protection. Emissions of such contaminants generally cannot be controlled by modification of the combustion process itself. However, modification of the combustion process may influence the form of the contaminates in such a way as to aid control by other, noncombustion means. Such contaminants were not a primary focus of this R&D planning study, but where combustion modifications could contribute to their control, appropriate research was identified. The fluidized-bed combustor using limestone for control of SO_x is a new combustion process or "combustion modification". One objective with such combustors is the integration of the combustion process with post-combustion or downstream control systems, rather than control through the combustion process itself. The fluidized-bed combustor was considered in this study insofar as R&D needs are related to the combustion process.

PHILOSOPHY OF R&D PLANNING

The 5-Year Combustion R&D Plan presented in this report is based on a philosophy of (1) matching technology gaps and needs with definable R&D tasks and (2) establishing priorities to provide effective allocation of available resources for supporting R&D projects. The early part of the study was devoted to identification of technology gaps and opportunities that could be exploited to contribute needed technology. After needed projects – called R&D opportunities later in this report – had been specifically defined, they were evaluated and ranked as to priority.*

Priority Ranking Rationale

The priority ranking rationale for applied-R&D opportunities included the following criteria:

- Pollutants affected
- Potential effectiveness in controlling the affected pollutants, considering nationwide emissions from energy-conversion combustion sources projected over a 20-year period
- Time to implementation of R&D results
- Likelihood of alternative noncombustion or competing downstream control systems.
- Costs of implementation.

Five priority levels, *A* through *E*, were established for applied R&D opportunities. A different priority scale, *1* through *5*, was established for fundamental-research opportunities, based on their relevance to applied R&D needs; through this method, fundamental-research opportunities that would support high-ranking applied-R&D opportunities were ranked highest.

Applying this priority rating methodology, the R&D opportunities were classified in priority categories and are presented in such a manner that the R&D Plan can be utilized in programming for various levels of resource allocations for the next 5 years.

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*The priority ranking rationale is summarized in Chapter II and is covered in more detail in Appendix A.

Emission Projections

To determine the potential effectiveness of a given R&D opportunity, or the benefit associated with a specified degree of pollutant control, projections of annual emissions over the next 20 years were used. These projections, shown in Figure I-2, are indicative of trends expected to occur if the present policy of emission control remained unchanged.

Implications of the Planning Methodology and Scope

A number of features of the planning methodology should be emphasized as they affect utilization of the Plan; these are briefly discussed as follows.

Type of Plan

The planning approach used results in a plan of the resource-allocation type falling in the "fixed-resources/variable goal" class. That is, the Plan is intended to maximize the achievement for any given research funding allocation. The plan is not of the "variable-resources/fixed goal" type designed to achieve, for example, a fixed reduction in pollutant emissions.

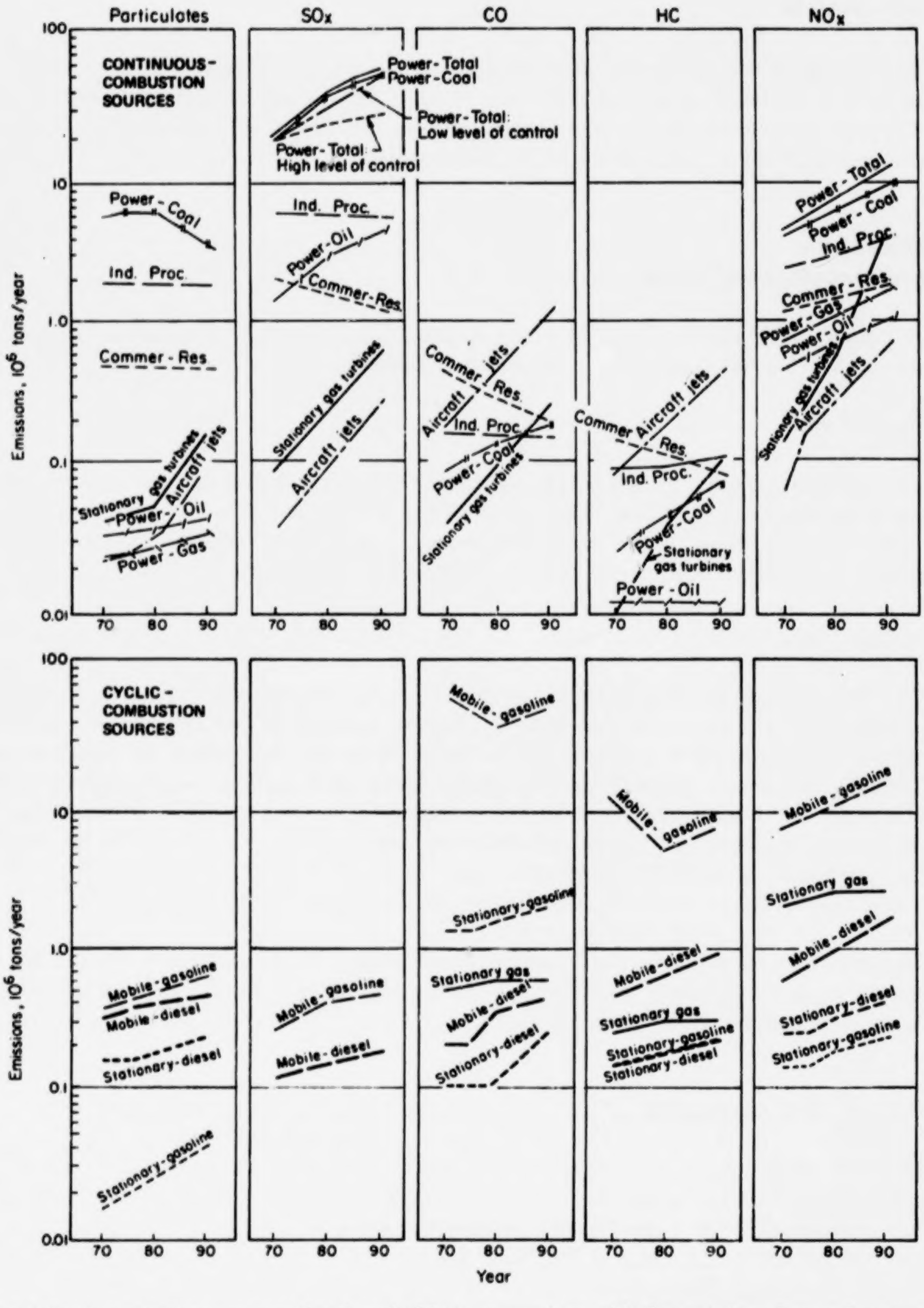
Relative Significance of Pollutants

The benefit associated with R&D opportunities for priority ranking in the applied-R&D areas is based on the fraction of the total pollutants emitted in the period 1970-1990 from energy-conversion combustion sources which could likely be controlled by undertaking the specified R&D. Nationwide projections of emission levels were used, as these emission data were the best available on a consistent base and are believed to be representative of the relative levels of combustion pollutants in typical industrialized urban areas. Should there be interest in considering the effect of more localized data where special health effects are clearly at stake, the planning rationale described could be modified to consider R&D priorities on this basis.

The priority ranking procedure applied equal weight to all pollutants. Should criteria be established at some future time regarding the relative significance of the pollutants, appropriate weighting factors can be incorporated into the priority ranking methodology in updating the Plan.

Parallel R&D Approaches

In some areas, the Plan includes parallel R&D approaches applying to the same general source and pollutant combination, even within the same priority category. In view of the overall needs in combustion R&D and the comparatively low level of current R&D effort, parallel approaches are considered justified at this time. As research progresses and as the Plan is updated with more fully defined factors entering the ranking process, one or more alternatives may be dropped.



The following emissions are considered negligible in comparison with the emissions from other sources:

SO_2 – gas-fueled power plants; gasoline, diesel, and gas stationary engines
CO – gas-fueled and oil-fueled power plants
HC – gas-fueled power plants
Particulate – gas stationary engines

Figure I-2. Projected Annual Emissions From Energy-Conversion Combustion Sources

Scope Limitation of Plan

It should be reemphasized that the scope of this R&D Plan is limited to modification of the combustion process for energy-conversion processes using prime fuels. The Plan does *not* include R&D for downstream control systems which may be applied to combustion sources, although the rationale for priority ranking of R&D for combustion modification includes an adjustment where there is a likelihood that downstream controls may be preferable in particular applications. Further, the Plan does *not* include R&D in other technical areas which may be needed to implement the results of the combustion R&D.

Thus the Plan represents only a part of the total R&D activities which can be directed toward a reduction of air pollution from combustion sources. Plans in other areas must obviously be considered together with this Combustion Plan in developing an overall R&D program for air-pollution control from combustion sources.

SUMMARY OF THE 5-YEAR R&D PLAN

The following pages provide a brief summary of the 5-Year R&D Plan – including technical content in areas of both applied R&D and fundamental research, recommendations relating to supporting activity, and a summary of estimated funding requirements by priority level for each program element.

TECHNICAL CONTENT OF THE PLAN

Technical background for R&D recommendations is covered in Chapters III through VIII for each of the areas constituting program elements of the Plan. Discussion in each of those chapters includes an appraisal of the status of combustion technology and identification of R&D needed to fill technology gaps for pollution control by combustion modification. Current R&D relevant to these areas is also tabulated, including both APCO projects and other R&D efforts.

In each of the program elements of the Plan, R&D opportunities or needed projects are defined as to technical objective, rationale and incentive, estimated R&D cost, and time to implementation. An evaluation of potential benefit and priority ranking is included with each R&D opportunity. R&D opportunities in each program element are grouped in priority categories according to the ranking evaluation and summarized in Chapter IX for all program elements by priority category.

Areas encompassed by R&D opportunities recommended within the various program elements are briefly outlined in the following section. Further details are found in the chapters.

Central-Station Power Plants
(16 R&D opportunities)

- Laboratory and field investigations of means to suppress NO_X by:
    - low-excess-air combustion
    - flue-gas recirculation
    - two-stage combustion
    - fuel properties.
- Development of new power-plant combustion concepts such as:
    - high-turbulence combustion
    - fluidized bed
    - gasification
    - electrochemical oxidation.
- Analytical and experimental investigations to promote means of retaining ash and slag within the furnace, or of altering the ash so as to promote its collection by downstream equipment.
- Development of research instrumentation and measuring conditions existing in central-station-power-plant furnaces.

Industrial Processing
(5 R&D opportunities)

- Programs aimed at NO_X reduction in:
    - rotary kilns for cement and lime production
    - glass-melting furnaces
    - open-hearth furnaces
    - regenerative melting furnaces
    - iron-sintering and iron-pelletizing processes.

Industrial Steam Generation and
Commercial and Residential Heating
(13 R&D opportunities)

- Development of Design Criteria
    - mathematical modeling of the combustion process
    - mixing, turbulence, combustion intensity, and temperature
    - internal and external recirculation
    - two-stage combustion
    - fluidized-bed combustion
    - PNA formation in fixed coal beds.

- Development of New and Improved Equipment Approaches
    - application of new design criteria
    - development of low-peak-temperature units.
- Investigation of Other Factors
    - transient conditions
    - additives and emulsions (residual fuel oil)
    - maintenance
    - more comprehensive emissions factors.

Continuous-Combustion Engines –
Gas Turbines and External-Combustion Engines
(5 R&D opportunities)

- Aircraft and Industrial Gas Turbines
    - design of primary-combustion zone to reduce NO_X emissions
    - design of secondary-combustion and dilution zone to reduce NO_X
    - development of criteria for reduction of CO, HC, and odor at idle and low power.
- Automotive Gas Turbines
    - development of a low-emission automotive-size gas-turbine combustor prototype.
- Automotive Rankine-Cycle Engine
    - development of low-emission combustors for Rankine-cycle automotive engines.

Reciprocating Internal-Combustion Engines
(10 R&D opportunities)

- Gasoline Engines
    - stratified-charge engines
    - lean-mixture operation and mixture preparation
    - generally applicable studies: wall quench, effect of lube oil, particulate and PNA formation.
- Diesel Engines
    - better understanding of combustion process for ultimate modifying of the diesel fuel-injection and combustion process so as to minimize emissions.
- General
    - kinetics of NO_X formation in IC engines

Fundamental and Broadly Applicable Combustion Research

'. (27 research opportunities)

- Physical Orientation
  - path-history relations in combustion
  - combustion of single and small number of droplets and particulates
  - combustion in fluidized beds
  - preparation of monographs on turbulence and droplet combustion.
- Chemical Orientation
  - chemistry of the formation and destruction of PNA, soot, and odorants
  - kinetics of HC – O_2 reactions
  - kinetics of NO_x – HC reactions
  - miscellaneous.
- Combined Physical and Chemical
  - global kinetic descriptions of combustion processes.

Recommendations Relating to Supporting Activity

- Coordination and Communication
  - monitoring of potentially useful combustion R&D by all sectors
  - preparation of bibliographies, organization of conferences, and broadening of report distribution to stimulate interchange of ideas
  - provision for interpretation of fundamental-research results for use in application.
- Program Planning
  - provision for periodic updating of the R&D Plan to reflect new technology and criteria.

SUMMARY OF FUNDING REQUIREMENTS FOR THE PLAN

Table I-2 summarizes estimated annual and 5-year funding levels for the various program elements of the Plan, breaking out the funding associated with each priority category. This funding includes provision for introducing R&D for new concepts or accelerating on-going R&D as a contingency for needs not now identified (designated as unranked priority N). Table I-3 summarizes 5-year funding levels by accumulating highest priority categories for each program element.

Funding levels estimated for each of the R&D opportunities in all program elements are listed by priority category in Chapter IX.

TABLE I-2. SUMMARY OF 5-YEAR COMBUSTION R&D PLAN BY PROGRAM ELEMENTS AND PRIORITIES WITHIN ELEMENTS

R&D Described in Chapter	Program Element or Source Category	Priority Level	Number of R&D Opportunities	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
III	Central-Station Power Plants	A	3	275	325	525	550	325	2,000
		B	4	700	1,450	1,850	3,900	4,000	11,900
		C	4	325	475	575	550	400	2,325
		D	3	300	350	400	250	300	1,600
		E	2	225	250	300	100	100	975
		N	1	–	250	350	400	500	1,500
		Total	17	1,825	3,100	4,000	5,750	5,625	20,300
IV	Industrial Processing	A	0	–	–	–	–	–	–
		B	0	–	–	–	–	–	–
		C	0	–	–	–	–	–	–
		D	0	–	–	–	–	–	–
		E	5	650	1,150	1,100	1,300	–	4,200
		N	1	–	50	50	50	50	200
		Total	6	650	1,200	1,150	1,350	50	4,400
V	Industrial Steam Generation and Commercial and Residential Heating	A	0	–	–	–	–	–	–
		B	3	375	425	475	475	350	2,100
		C	4	625	600	560	360	60	2,205
		D	4	700	600	525	150	150	2,125
		E	2	400	475	450	425	125	1,875
		N	1	–	150	200	250	250	850
		Total	14	2,100	2,250	2,210	1,660	935	9,155

TABLE I-2. (Continued)

R&D Described in Chapter	Program Element or Source Category	Priority Level	Number of R&D Opportunities	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
VI	Continuous Combustion Engines – Gas Turbines and External-Combustion Engines	A	2	700	500	400	400	–	2,000
		B	1	250	200	200	–	–	650
		C	1	200	200	–	–	–	400
		D	1	100	200	200	–	–	500
		E	0	–	–	–	–	–	–
		N	1	–	100	150	150	200	600
		Total	6	1,250	1,200	950	550	200	4,150
VII	Reciprocating Internal-Combustion Engines	A	3	700	760	700	–	–	2,160
		B	3	370	370	370	370	370	1,850
		C	1	100	100	100	–	–	300
		D	3	370	370	270	200	200	1,410
		E	0	–	–	–	–	–	–
		N	1	–	250	300	300	350	1,200
		Total	11	1,540	1,850	1,740	870	920	6,920
VIII	Fundamental and Broadly Applicable Combustion Research	1	4	800	675	575	575	575	3,200
		2	4	670	570	545	470	470	2,725
		3	6	625	600	600	600	425	2,850
		4	5	535	575	525	350	350	2,335
		5	8	740	635	410	160	100	2,045
		N	1	–	150	200	250	300	900
		Total	28	3,370	3,205	2,855	2,405	2,220	14,055
	Communications and Planning			300	300	300	300	300	1,500
	Overall Totals			11,035	13,105	13,205	12,885	10,250	60,480

TABLE I-3. SUMMARY OF 5-YEAR FUNDING ESTIMATES BY CUMULATIVE PRIORITIES FOR PROGRAM ELEMENTS OF THE 5-YEAR COMBUSTION R&D PLAN

		Estimated 5-Year R&D Costs, $1,000* *(Number of R&D opportunities is shown in parentheses)*						
		Priority or Cumulative Priorities						All Priorities
	Applied R&D	A	A-B	A-C	A-D	A-E	N	
Chapter								
III	**Central-Station Power Plants**	2,000 *(3)*	13,900 *(7)*	16,225 *(11)*	17,825 *(14)*	18,800 *(16)*	1,500 *(1)*	20,300 *(17)*
IV	**Industrial Processing**	–	–	–	–	4,200 *(5)*	200 *(1)*	4,400 *(6)*
V	**Ind. Steam Generation & Comm. & Res. Heating**	–	2,100 *(3)*	4,305 *(7)*	6,430 *(11)*	8,305 *(13)*	850 *(1)*	9,155 *(14)*
VI	**Continuous Combustion Engines**	2,000 *(2)*	2,650 *(3)*	3,050 *(4)*	3,550 *(5)*	3,550 *(5)*	600 *(1)*	4,150 *(6)*
VII	**Reciprocating IC Engines**	2,160 *(3)*	4,010 *(6)*	4,310 *(7)*	5,720 *(10)*	5,720 *(10)*	1,200 *(1)*	6,920 *(11)*
	Totals, Applied R&D	6,160 *(8)*	22,660 *(19)*	27,890 *(29)*	33,525 *(40)*	40,575 *(49)*	4,350 *(5)*	**44,925** *(54)*
		1	1-2	1-3	1-4	1-5	N	
VIII	**Fundamental Research**	3,200 *(4)*	5,925 *(8)*	8,775 *(14)*	11,110 *(19)*	13,155 *(27)*	900 *(1)*	**14,055** *(28)*
		A and 1	A-B and 1-2	A-C and 1-3	A-D and 1-4	A-E and 1-5	N	
	Totals by Funding Levels(a)	**10,860**	**30,085**	**38,165**	**46,135**	**55,230**	**5,250**	**60,480**

N Indicates unranked general provision for new concepts and opportunities.

(a) Totals of applied R&D and fundamental research in priorities shown, including supporting activities of communications and planning.

*Breakdowns of recommended funding by years (FY '71-'75) are shown in individual chapters and summarized in Chapter IX. (Tables IX-1 and IX-2).

Chapter II

APPROACH TO THE COMBUSTION R&D PLAN

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CHAPTER II

APPROACH TO THE COMBUSTION R&D PLAN

In a planning study that is concerned with the identification and selection of research investments, the resulting R&D plan is intimately related to the valuation and decision-making process used in developing the plan. Thus, the approach to this study is best discussed in terms of the planning rationale, as presented in the following section.

An additional factor important to the development of the 5-Year Combustion R&D Plan is the projection of pollutant emissions that serves to define the problem which the R&D Plan is designed to attack. As this factor becomes an integral part of the priority ranking methodology, it is also discussed within this chapter.

The overall structure of the report is outlined at the end of this chapter to facilitate the understanding of the arrangement of material and the terminology used in presenting the R&D Plan.

PLANNING RATIONALE

The rationale underlying a plan of this type should make it capable of being changed in a logical and internally consistent manner in response to changes in external factors. That is, the rationale makes the plan dynamic. Long-range plans for R&D programs must be designed for updating because the future cannot be fully predicted. The only aspect of the future to which a high probability can be attached is that criteria and technology will change; and changed conditions will inevitably alter the basis upon which any long-range plan is founded.

It is also true that an explicit planning methodology can incorporate only a limited number of factors entering into R&D investment decisions. The effects of these factors must always be supplemented by judgments made by the decision maker using the plan as a tool. It is essential that APCO staff who will be using the Plan presented in this report be critically aware of the factors underlying the planning rationale, so their supplementary judgments can be added in a knowledgeable and consistent way.

The planning rationale used in this study will be discussed in terms of four main subjects:

1. Primary goal of the Plan
2. Structure of the Plan
3. Derivation of content for the Plan
4. Methodology by which priority rankings were assigned to the R&D opportunities recommended in the Plan.

1. PRIMARY GOAL OF THE R&D PLAN

The primary goal for the R&D Plan is to achieve the greatest possible net reduction of pollutant emissions from energy-conversion combustion sources through support of a program of combustion R&D projects as constrained by certain guidelines as follows:

- Priorities must be given to program components to facilitate project selection with limited resources.
- Priorities must be based on combined considerations of potential benefits (emission reduction) and implementation costs.
- Time-urgency of emission reductions must be recognized.
- The assumed forecasting horizon for estimating benefits is 20 years.
- The established planning horizon for R&D funding is 5 years.

Although the goal statement is not complex, it implies a number of logical constraints which substantially affected the scope and thrust of the Plan. These implications are discussed below.

Implications of Program Goal

The Plan is to be of the resource-allocation type, falling in the "fixed-resources/variable-goals" class. That is, the Plan is to provide for the greatest possible pollutant emission reduction subject to the guidelines above (variable goal) for any given total funding allocation (fixed resource). Alternatively, the Plan might have been of the "variable-resource/fixed-goal" type with a specified amount of reduction to be achieved at a minimum (but unknown) funding level.*

The Combustion R&D Plan is so designed because the state of scientific knowledge concerning pollutant effects from combustion sources in general is still too imprecise to logically support or rationalize quantitative statements of requirements for reduction of specific pollutants. However, this situation is changing as air-pollution effects come under more intensive study. It may be desirable, as the advancing state of knowledge permits, to change the planning basis to the fixed-benefit type to achieve specific reductions of certain pollutants.

A complexity is introduced by the fact that cost-benefit planning techniques are called for in deriving project priorities, although the overall planning process is of the resource-allocation type. The costs considered in establishing priorities are implementation costs, whereas the resources to be allocated are the costs of supporting R&D for a 5-year period. It is important for correct understanding of the planning rationale to distinguish between these two types of costs and their entirely separate roles in the planning methodology.

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*In a general way, APCO's automotive-emissions control program falls in this latter category since it is based on achieving specified emission levels at definite times. However, the Plan developed during this study is confined to combustion R&D only. It is not believed, for example, that the 75/76 standards set for automotive emissions can be met through combustion modifications *only*. Thus, the 75/76 standards represent an unrealistic goal or "fixed benefit" for the combustion R&D activities being evaluated in *this* study. For this reason, and because a fixed-resource/variable-goal approach is more appropriate for pollutant sources for which specific emission standards have not yet been established, a fixed-resource/variable-goal approach was selected for this Combustion R&D Plan.

The only basis for crediting benefits to a suggested item of R&D is the ability to show that the results of the work are likely to bring about an actual reduction in the emission of pollutants.* For highly applied-development projects, it is possible to construct direct-relevance paths showing the plausibility of a pollution reduction being associated with the suggested R&D. In the case of fundamental research, there is no similar direct relationship for crediting benefits to the research; however, benefits can be credited to fundamental-research projects on the basis of their relevance to applied-R&D projects.

The planning guidelines included in the goal statement establish two "horizons". One is related to the design of the Plan itself; the other is concerned with the forecasting period used in assessing benefits. The planning horizon of 5 years was established by APCO. The forecasting horizon of 20 years (1970-1990) was chosen during the study as the best compromise that could be obtained between confidence limits of forecasting and the need to provide adequate time for R&D projects to be conducted and completed, to be implemented, and to accrue benefits.

The effect on the planning process of the definition of benefits as actual reductions in pollutant emissions is significant. A severe burden was placed on the forecasting part of the study by the requirement that the results of planned research be visualized in quantitative terms well beyond the period of initial implementation. Nonetheless, this is the only satisfying basis upon which to assess such benefits, and the principle was adhered to in the development of the Plan.

2. STRUCTURE OF THE R&D PLAN

The basic structure of the 5-Year Combustion R&D Plan was determined by APCO through the original specification that the Plan be established in terms of *programs, elements,* and *projects.* This specification defined the Plan as a 3-level structure and prescribed the nomenclature to be applied to each level. However, it was necessary during the planning study to give this structure specific meaning by deciding what was to be included in each level of the Plan and what the scope of each level was to be.

The *program* is defined here to include combustion R&D activities within the scope of this study recommended for support by Government agencies at the Federal level to fill gaps in the technology or to pursue promising R&D opportunities. Thus, the program is a complex of related activities and budgets. Each subunit of the program finds its place in the whole because it contributes in some definite way to the accomplishment of the goal that has been defined.

Program elements are the major subdivisions of the program. The program elements are established as pollution-source categories or application areas. Thus, one of the elements of the program is "central-station power plants"; another element is "reciprocating internal-combustion engines". Supporting fundamental research is treated as a separate element.

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*In considering such reductions, localized concentrations of pollutants (e.g., in a specific industrial city) were not taken into account; only the net reduction in the nationwide emission inventory was considered. Some emission sources (e.g., industrial processing), which make relatively small emission contributions on a nationwide-emission-tonnage basis, might have a much more significant local impact. However, including localized emission levels was beyond the scope of this study.

All items of R&D in the program that relate to a source category are grouped and budgeted as part of this element. Elements are defined in this way to make possible logical grouping of research subjects from an administrative and funding standpoint. There were relatively few cases in which applied R&D opportunities crossed element boundary lines. Elements might also have been defined as pollutants (e.g., SO_2, NO_x, etc.), but this would not have taken into consideration the interrelation of different pollutants affected by combustion modification. Elements might also have been defined by project type (i.e., all engineering test work might have been clustered together, all exploratory development, and so on), but this would not have taken full advantage of relevant technology.

Six elements were defined. Five are applied R&D elements, covering the source categories: (1) central-station power plants, (2) industrial processing, (3) industrial steam generation and commercial and residential heating, (4) continuous-combustion engines, and (5) reciprocating internal-combustion engines. The sixth element covers fundamental research or research that is broadly applicable to two or more application areas.

In the structure of the Plan, elements are subdivided into *projects*. The project is the basic unit of which the Plan is composed. At this level most of the R&D needs and opportunities were identified. Projects are referred to elsewhere in this report as *R&D opportunities* and the two terms are synonymous.

A project is considered to be a single stream of R&D activity aimed at producing a reduction in air pollution by virtue of some improvement or innovation through combustion R&D. Projects or R&D opportunities may consist of more than one definable task. These tasks may be conducted in parallel or in series, depending on the nature of the project. Multiple-task projects could be carried out under more than one contract, in-house program, or grant.

3. DERIVATION OF CONTENT FOR THE R&D PLAN

The content of the R&D Plan, consisting of R&D opportunities and their costs, was assembled as a result of conceptual and analytical study of a 13-man team. The staff was composed of technologists qualified in either the chemistry and physics of combustion or in the specialized technology of the source categories involved. The team developed the Plan's content in two steps:

- Identification of R&D opportunities on a provisional basis
- Screening and selection of R&D opportunities to be included in the Plan.

First, members of the team were assigned various aspects of combustion to study in detail. This was done to enable them to identify areas in which R&D is needed or where additional R&D is justified because of the new requirement to examine the combustion process from the standpoint of air pollution. The work was characterized as identification of "gaps" in the present knowledge of the field. In effect, the team members defined R&D opportunities that should be carried out from engineering and scientific viewpoints, and then reviewed current R&D to determine whether the field was adequately covered.

The experience of the individual members of the team was heavily relied upon in this phase of the project. In addition to a review of available information, contacts were made with pertinent sources in the technical community through correspondence and a number of field interviews.

Second, the suggested R&D opportunities were subjected to a judgmental screening process, and suggestions with insufficient merit to be included in the R&D Plan were eliminated. The screening criteria were:

- The research must give promise of filling a knowledge gap in a pollutant-problem area
- There must be plausible reason to anticipate that the results of the research will have potential for pollutant reduction

The screening process was carried out by committee action, with project team members participating as appropriate. The process was essentially one of committee questioning of the persons suggesting specific research ideas. Some ideas were rejected as violating one or more of the screening criteria. However, in most of the cases, the questioning procedure produced amplifications and refinements of the original suggestions. Therefore, the content of the R&D Plan can properly be regarded as the product of coordinated group effort, rather than the result of individual effort in compartmentalized fields of investigation.

All the R&D opportunities that survived this screening process are included in the 5-Year R&D Plan presented in this report. The committee activities described here were limited to selection of items for inclusion. No effort was made in committee to establish priority ranking at that point. However, the numerical values of planning factors which later entered into the priority rankings were reviewed and challenged through a similar committee approach.

4. METHODOLOGY OF PRIORITY RANKING

To make possible "fixed-resource" planning in advance of knowing the magnitude of resources actually available, it was necessary to arrange the content of the R&D Plan in a priority ordering. This makes it feasible, in applying the Plan, to consider any given funding level.

Applied R&D Priorities

In the case of the applied areas, priorities were assigned on the basis of:

- Relative potential for pollution reduction
- Relative cost to implement the results of the research
- Expert judgment.

Fundamental Research Priorities

For the fundamental research opportunities, priority ranking was handled somewhat differently than for the applied R&D opportunities. Fundamental research projects were assigned priorities based on:

- Relationship to applied-R&D opportunities, as expressed by relevance numbers.
- Expert judgment.

The methodology used to establish priority ranking of fundamental projects is discussed in Chapter VIII.

Methodology of Priority Ranking for Applied R&D

A detailed discussion of the methodology used to set priorities for applied R&D is presented in Appendix A. A brief summary of that methodology is given in the following paragraphs. The process is discussed in terms of the first two components of the evaluation basis: (1) relative potential for reducing pollution and (2) relative implementation costs. This is followed by a discussion of how these two components were combined to produce a single index of priority.

Potential for Pollution Reduction

Potential for pollution reduction is the measure of benefit associated with each identified R&D opportunity. Potential was estimated using a quasiquantitative procedure resulting in the calculation of a dimensionless Relative Potential Benefit Factor, B_k, which is the measure of benefit for a specific research opportunity, k. The numerical value of B_k was calculated by applying a group of four factors associated with pollutant sources and R&D opportunities to a Pollutant-Significance Factor, P_i, associated with each specific pollutant, i, and summing the results.

The numerical value assigned to P_i for a specific pollutant is defined as the relative benefit that would be associated with a 100 percent reduction in the projected uncontrolled emission of that pollutant from all energy-conversion combustion sources during the period 1970 to 1990 as compared with the same percentage reduction for other pollutants for the same period. Thus, P_i is a proxy for the "total problem" over the next 20 years presented by any one pollutant to which a given R&D opportunity might be related. In effect, then, P_i also represents the maximum possible benefit with respect to a specific pollutant related to an R&D opportunity if the outcome of the work enabled the elimination of all of that pollutant during the specified time period. As a result of discussions with APCO personnel, P_i was assumed to be unity for all pollutants. While the present state of knowledge concerning the relative significance of emission of each pollutant does not fully support any assumption as to values for P_i, the above assumption is considered reasonable for purposes of this planning study. When the state of knowledge permits a set of priorities to be established among the pollutants, new P_i's can be assigned reflecting these, and the R&D Plan can be adjusted accordingly.

The four source-category- and research-opportunity-associated factors are numerical measures of the limitations imposed by the following considerations on the reduction of pollutant emissions that could be achieved:

- Sources affected by the R&D opportunity and quantity of pollutant emissions from these sources
- Time to first implementation of the project's results
- Percent of pollutant reduction to be achieved
- Alternative controls not in the scope of combustion R&D, such as application of downstream controls.

Details concerning the emissions from the various sources are given in Appendix B.

Implementation Cost

Implementation cost for an R&D opportunity is defined as the total cost to society for implementing the results of the R&D by application to all installations within the source categories affected. In general, the magnitude of the implementation cost for an R&D opportunity would far exceed the cost of performing the R&D. Consequently, implementation cost was the only cost factor considered significant in establishing priority rankings.

Estimates of implementation costs were made by the project team on the basis of experience and judgment. These estimates were made in terms of increase or decrease in annual cost, i.e., dollars per year, and included consideration of:

- Changes in capital equipment costs
- Changes in fuel, additive, and power costs
- Changes in maintenance and operating labor costs.

However, because detailed cost studies were not made and because of the uncertainty necessarily involved in estimating costs far in the future and for items not yet developed, the estimates of implementation cost were translated into a "verbal portrayal" of the values (high, medium, low, and very low). These verbal portrayals represent the following approximate cost ranges:

- high: greater than \$1 billion per year ($>\$10^9$)
- medium: \$100 million to \$1 billion per year ($\$10^8$ to 10^9)
- low: \$10 million to \$100 million per year ($\$10^7$ to 10^8)
- very low: less than \$10 million per year. ($<\$10^7$)

Combination of Benefits and Costs for Priority Rankings

Ideally, it would be desirable to assign a unique priority index to each individual project in the total Plan (independent of program element). While such a numerical rating was utilized in the planning process, the individual ratings have been categorized for purposes of this report. The estimates and forecasts involved in the calculations of benefits and implementation costs were considered too uncertain to permit fine numerical discrimination in presenting the final results of the priority ranking. Instead, projects were clustered into five priority groupings – *A, B, C, D,* and *E.* The groupings have common significance for all the applied program elements since all applied R&D opportunities in these elements were evaluated on the same basis.

In assigning each R&D opportunity to one of the five priority groupings, both potential for pollution reduction, as measured by B_k, and the general magnitude of possible implementation cost, as indicated by the verbal portrayal of cost, were considered. However, greater emphasis was placed on potential for air-pollution reduction than on possible implementation costs because, at this time, benefit estimates are considered more important (and more reliable) than implementation-cost estimates. Furthermore, the need for actually funding the implementation of a given project cannot possibly arise until the research is nearing completion. At that time a far better appraisal of both costs and benefits can be made. Therefore, although implementation cost should be accounted for in establishing priority, it is logical to reduce its significance compared with the significance of expected benefits.

The procedure used to accomplish the combined priority ranking was to assign a numerical value on a logarithmic scale, i.e., 1, 2, 4, and 8, to each of the four implementation cost categories, i.e., *very low, low, medium, and high,* respectively. The B_k for a given R&D opportunity was then divided by either 1, 2, 4, or 8, depending on the implementation cost category into which the opportunity was estimated to fall. The resulting modified B_k values were then rank ordered from highest to lowest, and cutoff points judgmentally selected to define priority groupings *A, B, C, D, and E.*

While this procedure for including consideration of implementation cost does not permit the R&D opportunities rated lowest with respect to potential for pollution reduction to be placed in the *A*-priority group, it does permit some modest variations in priority ranking. For example, some R&D opportunities with medium values for B_k are ranked in either *B, C, or D* priority groups, depending on whether they are estimated to have *very low, low, or medium* implementation costs.

It should be noted that the above procedure makes no specific recognition of the combustion R&D opportunities that are competing, or even mutually exclusive in the sense that they represent alternative approaches to combustion modification for controlling the same pollutants from the same sources. Although this feature necessitates some care on the part of the decision maker employing the Plan, such conflicting R&D opportunities were retained because they represent alternative schemes whose relative merits cannot be distinguished at this time, other than as accounted for in the priority rankings. Preliminary or exploratory work on the alternative schemes would make possible further discrimination at some future time, permitting a change in priorities or the elimination of distinctly unpromising R&D opportunities from the Plan.

EMISSION DATA AND PROJECTIONS

Essential needs of the R&D planning methodology are: (1) knowledge of the present levels of pollutant emissions and (2) reasonable predictions of what emission levels may be expected in the future if present trends continue. In response to these needs, a compilation was made of the latest available information on emissions from combustion sources (1966), and available projections of emissions between 1970 and 1990 were obtained. Most of the emissions data and projections were obtained from APCO sources; when no projections were available, needed data were derived by Battelle staff members. These projections were used to determine the quantity of pollutant emissions affected by each R&D opportunity.

A summary of the data compilation and of the emission projections follows. Additional data are presented in Appendix B and the projected pollutant values used in the priority ranking derivations are tabulated in Tables B-1 through B-5.

POLLUTANT EMISSION INVENTORY

Table II-1, an inventory of U.S. pollutant emissions for 1966, is presented to illustrate the present level of emissions for various combustion sources. The table is based primarily on data developed and collected by the APCO Division of Air Quality and Emission Data (DAQED). These DAQED data have been published in the *Nationwide Inventory of Air Pollutant Emissions, 1968.**

In this study, only portions of the detailed APCO breakdowns that apply to energy-conversion combustion sources were used. For instance, the "Industrial Processing" category in Table II-1 does not include emissions from the manufacture of coke, nor does it include pollutants arising from materials being processed; for example, data are not included for iron oxide particles emitted during steel processing. Also, piston-aircraft emissions have been included in the "Mobile Gasoline" category with automobile emissions as part of IC-engine emissions; jet-aircraft emissions appear in the "Gas Turbine" category.

The method generally used to determine nationwide pollutant emissions employs tables of fuel usage (or vehicle miles) broken down by type of fuel user. The amount of fuel consumed (or the number of vehicle miles) is multiplied by an emission factor appropriate for the combustor, engine, or boiler. Fuel-usage and vehicle-miles data can be obtained from the U.S. Census Department's annual *Statistical Abstract of the United States*. In general, the emission factors used to generate data contained in Table II-1 were taken from the *Compilation of Air Pollution Emission Factors* (2nd Printing, 1969).** DAQED has used factors different from these in cases where more recent or detailed information within APCO has indicated that the published values are in error. For instance, DAQED has made allowances for the variation of emissions with automobile age.

**Nationwide Inventory of Air Pollutant Emissions, 1968,* USDHEW Public Health Service Publication No. AP-73, Raleigh, North Carolina (1970), 36 pp.

**Duprey, R. L., *Compilation of Air Pollutant Emission Factors,* Second Printing, USDHEW Public Health Service Publication No. AP-42, Raleigh, North Carolina (1968), 67 pp.

Table II-1 — Nationwide Inventory of Pollutant Emissions by Class of Source(a) 1966, 10^6 Tons/Year

Pollutants	Total, All Sources	Total, All Combustion Sources	Total, All Energy Conversion Combustion	Continuous Combustion for Energy Conversion								Cyclic Combustion for Energy Conversion					Other Non-ECC	
				Central-Station Power Plants						Gas Turbine		Mobile IC Engines		Stationary IC Engines				
				Coal	Oil	Gas	Industrial Processing	Industrial Steam Generation	Commercial & Residential Heating	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas	Solid Waste Incineration	Miscellaneous Combustion
1. Products of Incomplete Combustion																		
Combustible Particulate(c)	–	–	3.3	0.6	<0.1	<0.1	0.2	1.2	0.3	<0.1	<0.1	0.4	0.5	<0.1	0.1	n	–	–
CO	102.1	91.3	65.8	0.1	n	n	0.1	0.1	0.7	<0.1	0.3	62.3	0.2	1.4	0.1	0.5	7.6	17.9
Gaseous HC	31.5	27.9	17.8	<0.1	<0.1	n	n	0.1	0.2	<0.1	0.1	16.4	0.6	0.1	0.1	0.2	1.5	8.6
PNA(b)	12.	11.2	7.2	n	n	n	0.3	n	6.5	–	–	0.4	n	n	n	n	1.0	3.0
2. NO_x	18.9	18.6	16.4	2.7	0.3	0.5	0.4	2.0	0.8	0.1	0.1	6.3	0.9	0.1	0.2	2.0	0.5	1.7
3. Combustion-Improving Additives																		
Lead(d)	0.25	0.21	0.21	n	n	n	n	n	n	n	n	0.21	n	<.01	n	n	n	n
4. Fuel Contaminants																		
SO_x(d)	30.9	23.5	22.9	13.5	1.0	n	1.1	4.4	2.6	0.1	<0.1	0.2	<0.1	n	n	n	0.1	0.6
Ash (Noncombustible Particulate)(c)	–	–	6.8	4.9	<0.1	n	0.2	1.4	0.3	n	n	n	n	n	n	n	–	–
5. Total Particulate	28.6	21.0	10.1	5.5	<0.1	<0.1	0.4	2.6	0.5	<0.1	<0.1	0.4	0.5	<0.1	0.1	n	1.0	9.9

(a) Sources of data: APCO/DAQED and DPCE plus APCO (NAPCA) Reports.
(b) PNA shown in 10^3 tons/year.
(c) Combustible particulate apportioned from total data by Battelle judgment.
(d) Emission values for Lead are for 1967.

–, not available.
n, emission considered negligible.

FORECASTS OF POLLUTANT EMISSIONS

Figures II-1 through II-5 depict the trends of pollutant emissions from energy-conversion combustion sources that can be expected between 1970 and 1990. The curves are illustrative of the pollutant projections used in evaluating the R&D opportunities identified in this report. Data upon which these figures are based are presented in Tables B-1 through B-4.

Sources of Data for Forecasts

Emission projections presented in Figures II-1 through II-5 are based primarily on APCO sources. When the APCO emission forecasts were obtained, they had not yet been collected in one document. APCO's Division of Process Control Engineering (DPCE) is engaged in developing projections for emissions of SO_X, particulates, and NO_X from stationary sources. When completed, these DPCE projections are to be combined with those already developed by DAQED. Other forecasts included in Figures II-1 through II-5 are from reports completed for NAPCA by Northern Research and Engineering Corporation* and Esso Research and Engineering Company**. In cases when APCO forecasts did not cover all of the categories of interest, predictions were developed from the same fuel-usage (or vehicle-mileage) sources used for the projections by APCO.

In Table II-1, "total particulate" is split into "combustible particulate" and "ash (non-combustible particulate)" in accordance with published data or by the judgment of the Battelle team. These particulate data follow the definition of particulate matter assumed by Duprey in *Compilation of Air Pollutant Emission Factors.****

Some Factors Influencing Emission Trends

In Figures II-1 through II-5, the curves showing rising trends reflect forecasts of increased demands for energy and transportation. The curves showing projected decreases in emissions with time are based on predicted switching to fuels emitting lesser amounts of pollutants or on anticipated emission controls.

The changes in curve slope are the result of various conflicting influences – e.g., more stringent regulations and better control devices on the one hand and increased number of pollutant-producing units on the other. In Figures II-2 and II-3 the implementation of the 1970 regulations concerning automobile emissions of HC and CO is reflected in downward trends for these emissions until the projected increase in the automobile and small-truck population causes emissions to increase. Decreased emissions of particulates from coal-fired power plants due to the increased use of control devices such as electrostatic precipitators on both new and existing plants have been predicted by DPCE. However, Figure II-1 shows that it will probably be several years before implementation will be sufficient to cause a downward trend in the overall national emission curve for this source.

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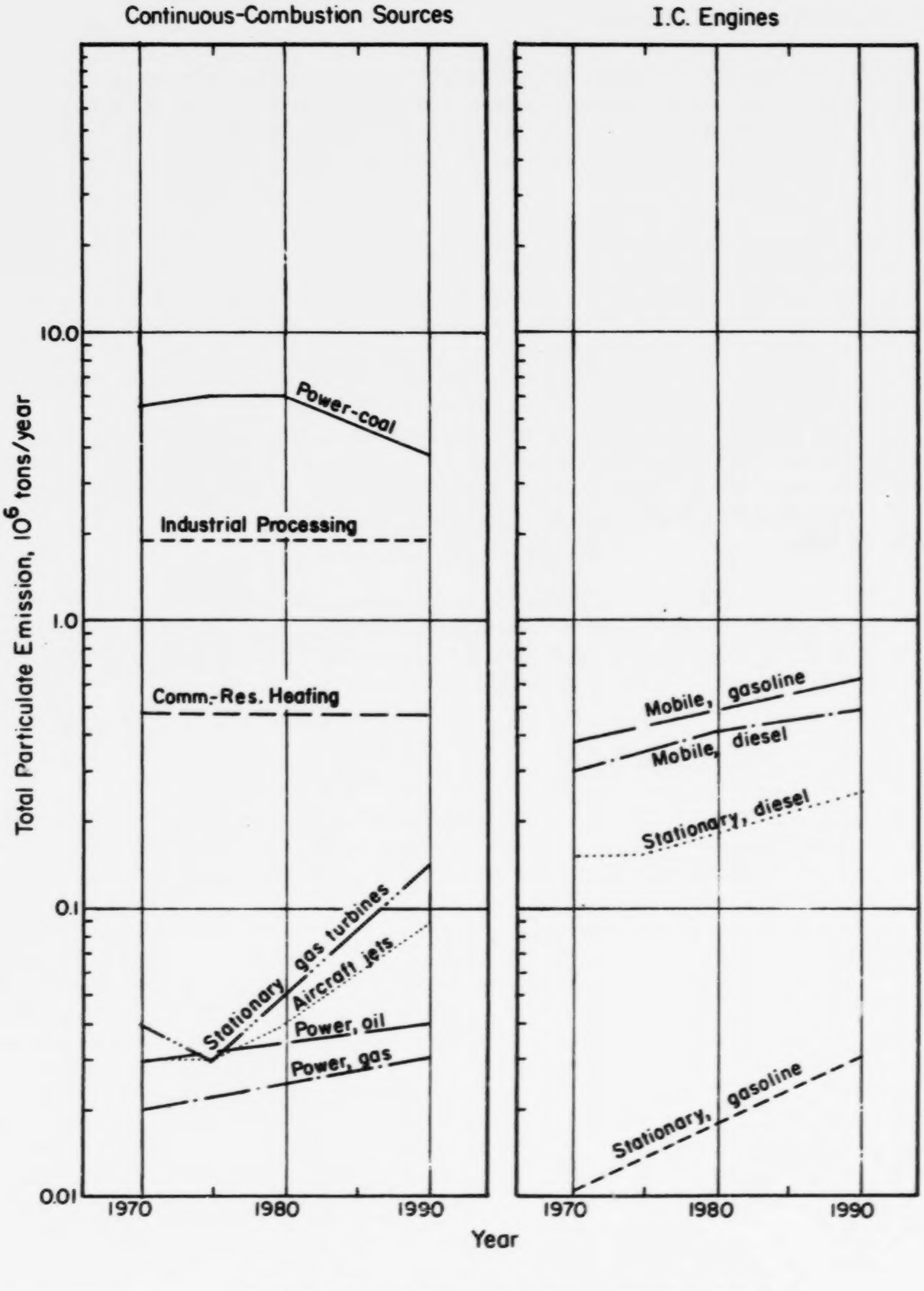
*Final Report to National Air Pollution Control Administration, *Nature and Control of Aircraft Engine Exhaust Emissions,* from Northern Research and Engineering Corporation (November, 1968), 388 pp, Contract No. PH 22-68-27.

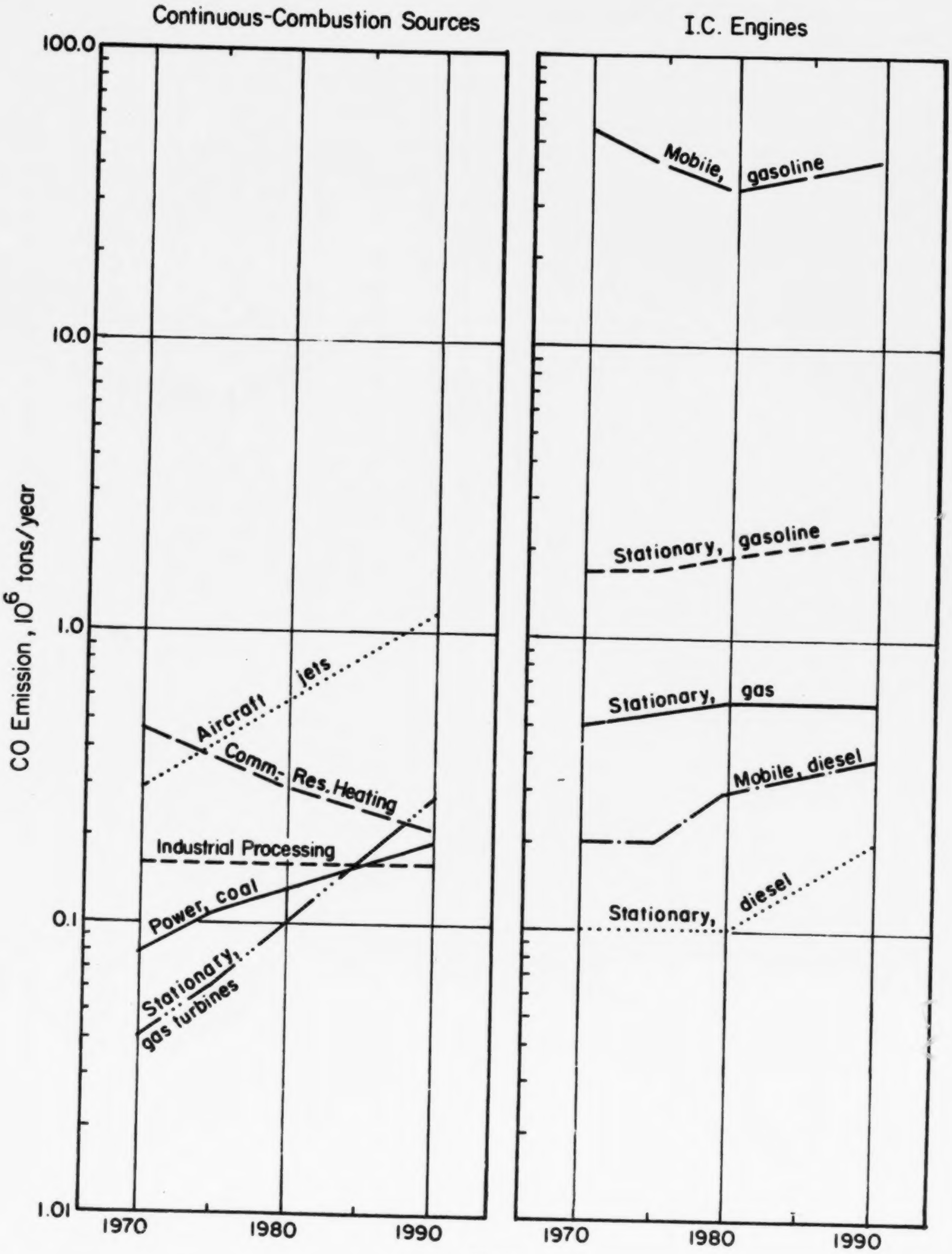
**Final Report, Volume II, to National Air Pollution Control Administration, *Systems Study of Nitrogen Oxide Control Methods for Stationary Sources,* from Esso Research and Engineering Company, Government Research Laboratory (November, 1969), Contract No. PH-22-68-55.

***Op. cit.



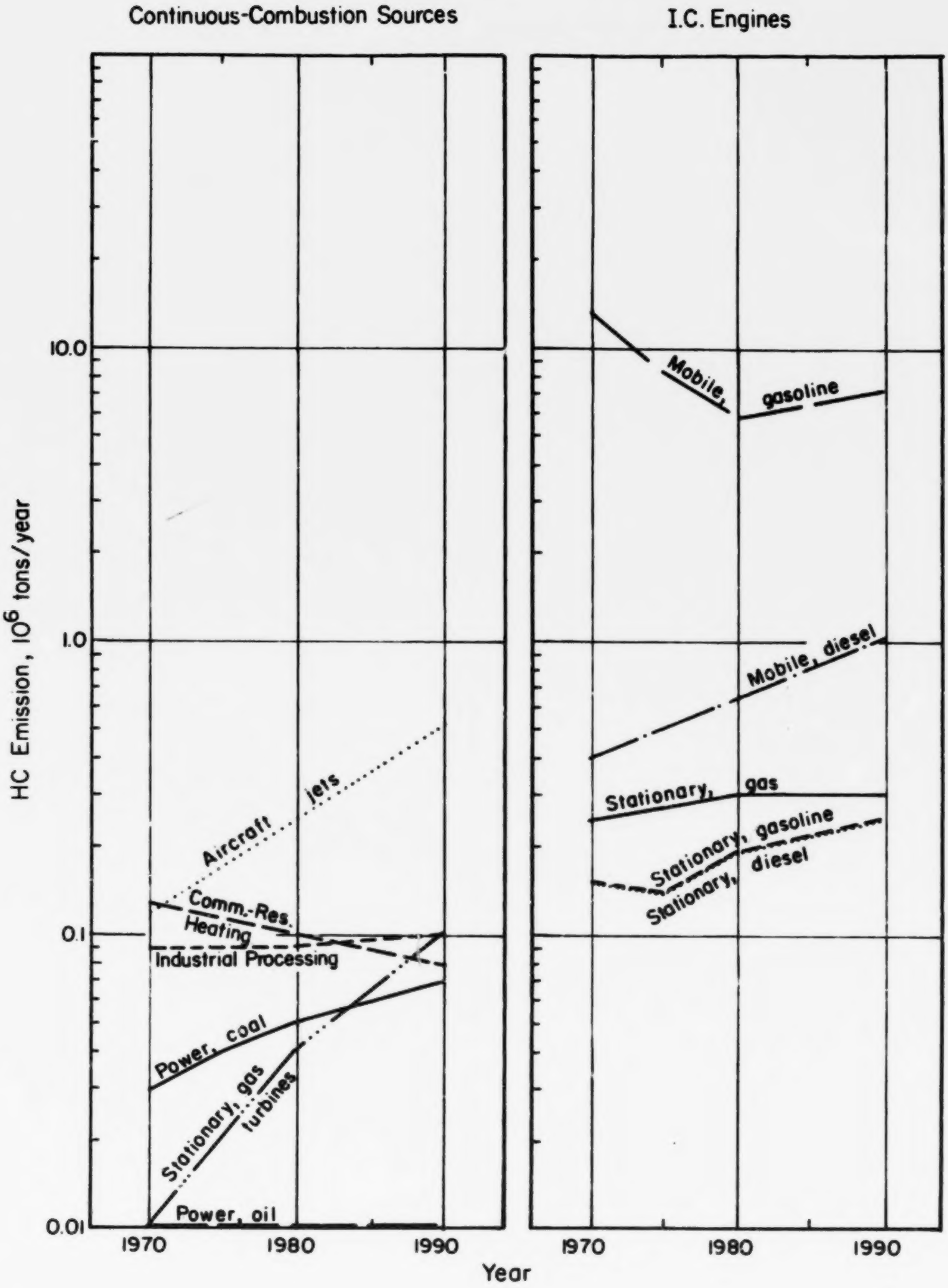
Particulate from stationary gas engines considered negligible

Figure II-1. Projected Annual Emissions of Total Particulate from Continuous- and Cyclic-Combustion Sources



CO from gas- and oil-fueled power plants considered negligible

Figure II-2. Projected Annual Emissions of CO from Continuous- and Cyclic-Combustion Sources



HC from gas-fueled power plants considered negligible

Figure II-3. Projected Annual Emissions of HC from Continuous- and Cyclic-Combustion Sources

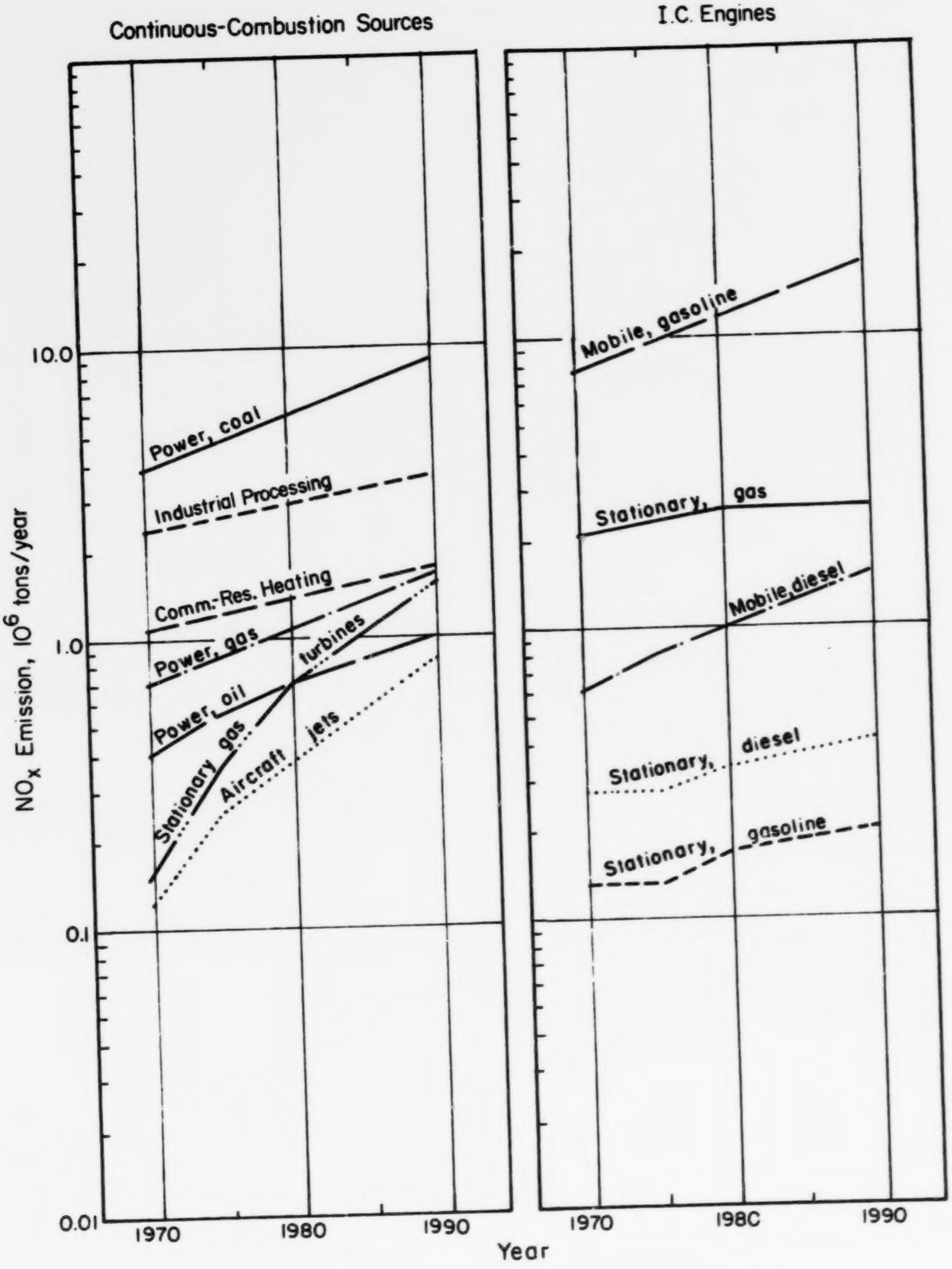
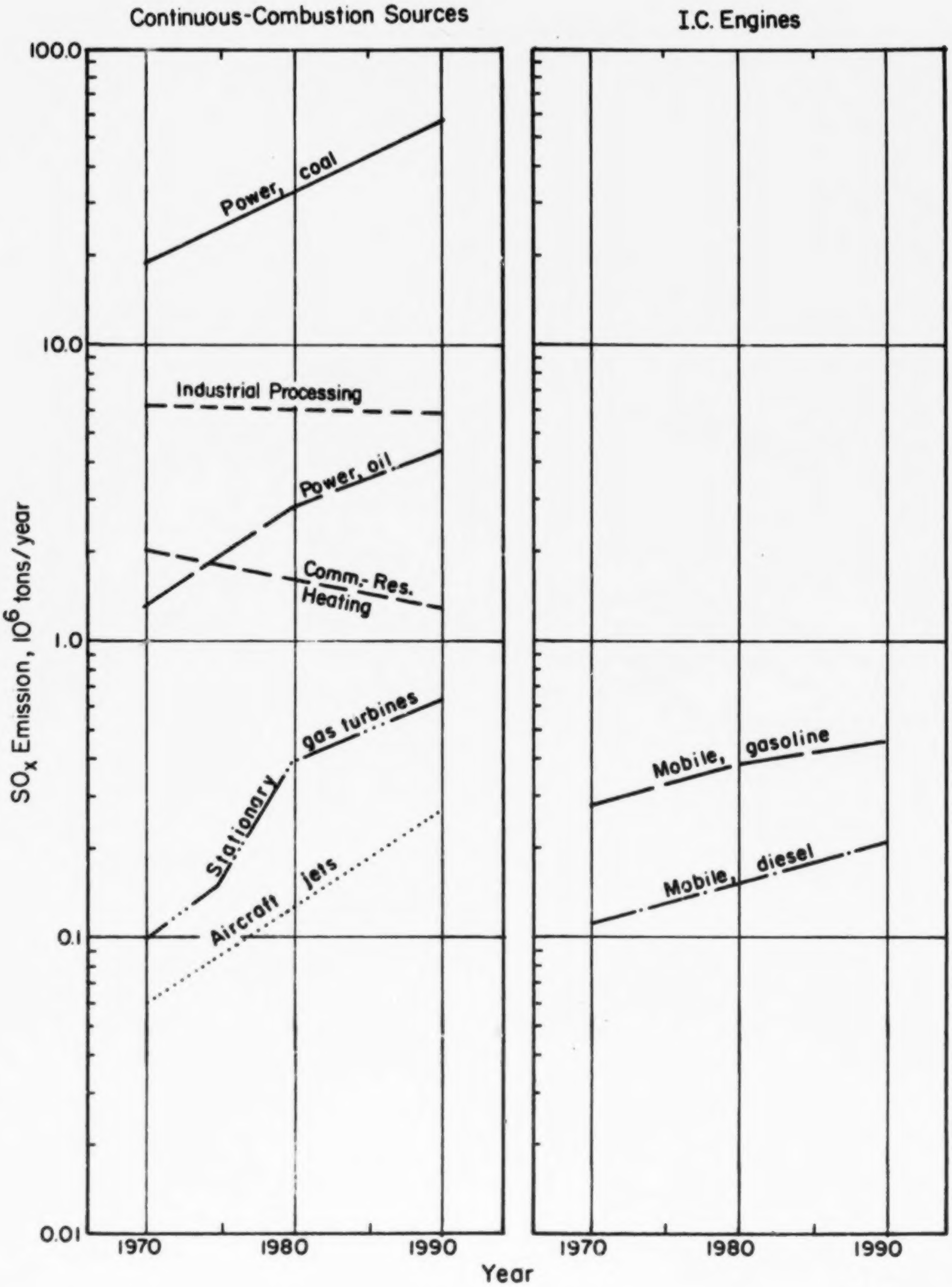


Figure II-4. Projected Annual Emissions of NO$_x$ from Continuous- and Cyclic-Combustion Sources



SO$_x$ from gas-fuel power plants and gasoline, diesel, and gas stationary engines considered negligible

Figure II-5. Projected Annual Emissions of SO$_x$ from Continuous- and Cyclic-Combustion Sources

In the case of aircraft emissions, the NAPCA report by Northern Research and Engineering Corporation* forecasts a reduction of particulate emissions and an increase in NO_X emissions, reflecting the installation of smokeless jet engines. The reduction in particulate emissions from jet aircraft will only temporarily retard the rise of the national pollution emission curve for this source. If the increase in air travel continues at the rate of growth experienced in recent years, even a reduction of 50 percent in individual aircraft pollutant emissions will be overcome by the overall increase in jet engine population and the greater mileage flown.

Confidence Level of Forecasts

As mentioned previously, all the emission projections – whether derived by APCO or Battelle – were calculated by multiplying appropriate emission factors for various pollutant sources by projections of fuel usage (or mileage). There must always be some hesitancy in claiming that the emission factors used are undeniably correct, as they can vary with the type, age, and operating mode of the equipment population assumed. They may also vary in future years as a result of developments in processes, fuels, equipment, or operating patterns.

Even more uncertain are the projections of fuel usage. They are generally developed by extrapolating past trends in usage, population growth, or demand, all of which are known to change. For instance, in the case of the Bureau of Mines forecast of energy demand,** the derivation was based on trends prevailing up to 1963; by the time the projections were published in 1968, some of the predictions were already known to be inaccurate. DPCE, to make its current predictions of emissions from stationary sources as nearly accurate as possible, has obtained and employed more recent published and unpublished fuel-usage data from the Atomic Energy Commission and the Federal Power Commission.

Because of the uncertainties in these inputs to the development of emission projections, the projections must be considered as having only limited accuracy. Most suspect of all are the absolute magnitudes of levels projected. However, the trends shown in Figures II-1 through II-5 are probably indicative of what will occur if the present policy of emission control remains unchanged.

For this planning study, the aim in developing these breakdowns of emissions and in deriving the projections has been to define the problem of combustion emissions in relation to the overall air-pollution problem and the relation of the emissions from various combustion sources to each other. Even in view of the uncertainties of the projections, this aim has probably been achieved.

The projections in Figures II-1 through II-5 afford the opportunity to develop a semi-quantitative method of placing priorities on possible combustion R&D opportunities. Using these projections, estimates can be made of the reductions in emissions that would result if selected R&D opportunities were funded to fruition.

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*Op. cit.

**Morrison, W. E., and Readling, C. L., *An Energy Model for the United States Featuring Energy Balances for the Years 1947 to 1965 and Projections and Forecasts to the Years 1980 and 2000*, Bureau of Mines Information Circular IC 8384 (July, 1968).

STRUCTURE OF REPORT

Chapters Covering Program Elements of the R&D Plan

Major combustion-source categories or application areas are discussed in separate chapters within this report as they pertain to the development of the Combustion R&D Plan. Fundamental research is covered separately, but the relevance of fundamental research opportunities to the application areas is indicated. Chapter designations are as follows:

Applied R&D for Major Source Categories

Continuous-Combustion Sources:

- Chapter III. **Central-Station Power Plants**
- Chapter IV. **Industrial Processing**
- Chapter V. **Industrial Steam Generation and Commercial and Residential Heating**
- Chapter VI. **Continuous-Combustion Engines – Gas Turbines and External-Combustion Engines**

Cyclic-Combustion Sources:

- Chapter VII. **Reciprocating Internal-Combustion Engines**

Fundamental Research

- Chapter VIII. **Fundamental and Broadly Applicable Combustion Research**

5-Year R&D Plan

- Chapter IX. **Summary of the 5-Year Combustion R&D Plan**

Thus, Chapters III through VIII cover separate program elements within the 5-Year Plan, and Chapter IX provides a summary.

The Appendixes cover additional details of the planning rationale and priority ranking procedure, plus emission data and projections utilized in the ranking evaluation.

Organization of Material Within Elements of the R&D Plan

Applied Program Elements. Each of the chapters on combustion processes for the major source categories includes material which provides the following coverage:

- Definition of chapter scope, and general background
- Pollutants of principal concern within the source category
- Emission levels from combustion processes with present practice
- Emission levels attainable with latest technology or potentially attainable with promising approaches to combustion modification
- R&D needed to fill technology gaps
- Identification of current R&D relevant to emission control by combustion modification (including tabulation of projects)
- Description of R&D opportunities recommended for the 5-Year Plan, with funding by fiscal year
- Evaluation and priority ranking of R&D opportunities
- Summary of R&D opportunities by priorities.

Fundamentally Oriented Program Element. Chapter VIII, covering fundamental and broadly applicable combustion research, is organized in a similar manner, except research needs in areas of *combustion physics* and in *combustion chemistry* are discussed in separate sections. Current research is identified as pertinent to both areas, and descriptions of research opportunities recommended for the Plan cover both areas.

Also covered in Chapter VIII is the methodology used for priority ranking of research opportunities considered to be fundamental and broadly applicable; in this procedure the priority ranking is based on relevance of a given "fundamental" research opportunity to specific needs identified under the applied program elements.

Survey of Current R&D Relevant to the Plan

The study provides an overview of current R&D effort by both the private and governmental sectors of the research community. A tabulation of current R&D appears in each of the chapters covering a program element. It must be recognized that availability of information on R&D conducted by private industry is limited by proprietary considerations. In the governmental sector, R&D funded by APCO (NAPCA) and other agencies in fiscal years 1968 through 1970* has been considered as *current R&D*; the tabulations include in-house programs, contracts, and grants.

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*FY '71 information is included, where available.

Tabulations of current R&D. These tabluations include:

- Contract or project title
- Sponsoring organization and contract number
- Research organization conducting the work
- Principal investigator(s)
- Objective or scope
- Funding (where known).

Sources of Information. Current R&D was identified and information was obtained from a variety of sources, including:

- APCO contracts lists and information provided by the APCO staff
- Information provided by searches of DOD projects through the Defense Documentation Center (literature searches and *DOD work unit summaries),* searches of NASA reports, searches of other government research projects compiled by the Interagency Advance Power Group, and data sheets on recent and current research by the Smithsonian Institution's Science Information Exchange
- Information assembled by the Center for Air Environment Studies, at Pennsylvania State University, as part of an extensive NAPCA survey of current research in air pollution*
- Information on foreign R&D activities from the NAPCA Profile Study on Air Pollution Control in Foreign Countries, being conducted by Esso Research and Engineering Company**
- Discussions and correspondence with personnel of government agencies, trade associations, industrial companies, research organizations, and universities
- Follow-up discussions with investigators known to the Battelle staff, or identified through the above sources, or identified by authorship of papers in the literature.

The tabulations of current R&D projects in the chapters should be viewed within the limits of the above sources and, thus, cannot be considered a complete listing, particularly of R&D undertaken by private industry. However, the survey is considered adequate for the purpose of this planning study, as information which is obscure or proprietary at this time may never be published, or publication may be delayed beyond its usefulness for the 5-Year R&D Plan.

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*Through cooperation of the Center, information sheets as supplied by survey respondents were reviewed and screened by Battelle staff to identify combustion-oriented projects. The completed survey was later published by PHS as *Guide to Research in Air Pollution, 1969,* under Contract CPA 22-69-37.

**Through cooperation of Esso R&E, indexed information cards from their survey being compiled at Esso's laboratories at Abingdon, England, were screened by personnel of Battelle's London office for relevant combustion R&D. The completed study will be published soon under NAPCA Contract CA 22-69-88.

Explanation of Format for Displaying Evaluations of Applied-R&D Opportunities

The R&D opportunities identified and recommended for the 5-Year Plan are described at the end of each of the applied R&D chapters covering major source categories (Chapters III through VII). These descriptions include:

- **Technical objective and approach**
- **Rationale and incentive.**

The description of each applied R&D opportunity is followed by tabulated information concerning the R&D opportunity.

Figure II-3 is a sample format intended to illustrate the tabulated material and permit explanation of its features.

Figure II-3. Sample Format for Evaluation Summaries of Applied R&D Opportunities

Estimated R&D Cost & Time

R&D Cost Range, 1000's: \$ _____ – \$ _____

R&D Time Range: Years

Recommended 5-year Funding, 1000's: FY '71-'75

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, \$1000's	X**			Recommended			Provision for funding on-going R&D

Evaluation

Sources Affected: Categories: e.g., Central-Station Power Plants or Diesel Engines

Relative Potential Benefit (overall rating): Very Low → Very High

Pollutants Affected	CP†	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range										–
Expected										–
Fraction of ECC Emissions Affected										–
Noncombustion Controls Factor										–
Relative Potential Benefit Factor										B_k Summation

Implementation Time, years: Range most likely: Est.

Relative Implementation Cost: Very Low, Low, Medium, or High

Relative Priority Rating: A, B, C, D or E

Notes: * shown on \$ level of Recommended 5-Year Funding or '76+ funding indicates that R&D may include one or more field demonstrations to apply results of the R&D.

X indicates that one or more APCO current projects (defined as active in 1969 or 1970) are relevant to the combustion R&D opportunity described.

†CP = combustible particulate.

Items incorporated in the format illustrated in Figure II-3 are as follows:

- Estimates of R&D time and cost
  - Ranges likely in time and cost, due to imprecision in forecasting these factors
  - Recommended funding by fiscal year and 5-year total.
- Relevance of one or more current APCO projects to this R&D
  - Shown by "X" in FY'69-'70 Column*
    (Funding levels for current APCO R&D are not shown due to difficulty in apportioning fractions of current projects which are relevant to several identified R&D opportunities).
- Sources Affected
  - Categories of pollutant sources to which this R&D is applicable.
- Relative Potential Benefit (overall rating)
  - A verbal descriptor of the potential value of the R&D in reducing pollutant emissions – expressed as Very Low, Low, Medium Low, Medium, Medium High, High, or Very High. This is a verbal description of the numerical Relative Potential-Benefit Factor, B_k.
- Pollutants Affected
  - Entries in the table within a specific pollutant column indicate that the R&D affects emissions of that pollutant
  - "CP" refers to combustible particulate.
- Percentage Reduction, Range
  - The percentage reduction in pollutant emission from the specified sources resulting from application of the R&D – expressed numerically as a range from low to high.
- Percentage Reduction, Expected
  - The expected reduction in pollutant emission from the specified sources resulting from this R&D.

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*In cases where a given R&D opportunity is relevant to other opportunities or to current R&D projects, the key designations of the relevant projects are shown above the title of the given opportunity.

- Fraction of ECC Emissions Affected
  - The fraction of the total pollutant emission from all energy-conversion-combustion sources summed over the period 1970-1990 which can be affected by this R&D.
  - This fraction is determined by both the sources affected (based on data presented in Table B-5) and the time required to complete and implement the results of this R&D.
- Noncombustion-Controls Factor
  - A factor which allows for the likelihood that competing controls (e.g., downstream controls) may be applied to the sources, thus reducing the benefit that could be accomplished if this R&D opportunity were successfully completed.
- Relative Potential-Benefit Factor
  - The product of: (Percentage Reduction, Expected), (Fraction of ECC Emissions Affected), and (1.0 minus Noncombustion Controls Factor). This value presents a relative-numerical measure of the reduction in total ECC emissions of that pollutant over the 1970-1990 period which might be ascribed to this R&D.
  - The column headed "Σ" is the summation of the Relative Potential-Benefit Factors for each pollutant. This sum is the single overall numerical measure of the benefit expected from this R&D and is identified elsewhere as B_k.
- Implementation Time, years
  - The total elapsed time between beginning the described R&D and making the first field implementation of the results – expressed both as a range and a most-likely value.
  - This factor is used in establishing the Fraction of ECC Emissions Affected.
- Relative Implementation Cost
  - The estimated cost of implementing the R&D results expressed by the verbal descriptors Very Low, Low, Medium, or High.
- Relative Priority Rating
  - The priority class, ranging from A (high) to E (low), in which the R&D opportunity is placed by the ranking procedure.
  - The priority ranking of the R&D opportunities is based on a combination of the Relative Potential-Benefit Factor, B_k, and a measure of the Relative Implementation Cost.

Details concerning the individual items and the procedures used to derive the Relative Potential-Benefit and the Relative Priority Ranking are discussed in Appendix A.

SUMMARY OF PRIORITIES FOR THE 5-YEAR PLAN

At the end of each chapter, the R&D opportunities and funding requirements within the particular source category or program element are summarized by priority class. A consolidated summary of R&D opportunities and funding requirements for all applied program elements (and fundamentally oriented research opportunities as a group) is presented by priority class in Chapter IX. Summary tables in Chapter IX present estimated funding levels by year, by 5-year total, by priority class, and by program element.

Chapter III

CENTRAL-STATION POWER PLANTS

William T. Reid
Albert E. Weller

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CHAPTER III

CENTRAL-STATION POWER PLANTS

SCOPE OF CHAPTER AND BACKGROUND

This chapter is concerned with potentially valuable combustion research to reduce the principal air pollutants emitted by large central-station power plants (100 MW and larger) having fossil-fuel-fired steam generators. These pollutants are: (1) products of incomplete combustion – i.e., partially oxidized fuel emitted as combustible particulate matter, carbon monoxide, and polynuclear aromatics (PNA); (2) nitrogen oxides; (3) sulfur oxides; and (4) fly ash and particulates formed from fuel contaminants and noncombustible additives. Thus far only particulate emissions have been controlled to any appreciable extent and this, in great part, has been by use of mechanical collectors and electrostatic precipitators downstream of the combustion process.

Table III-1 shows the emission of various pollutants from central-station power plants in terms of the total emission from all energy-conversion combustion sources burning prime fuels.

Table III-1. Pollutant Emissions From Central-Station Power Plants*

Pollutant	Contribution to Nation-wide ECC Emissions, percent			
	Coal	Oil	Gas	Total
Products of Incomplete Combustion				
Combustible Particulate	18	<1	<1	18
CO	<1	nil	nil	<1
Gaseous HC	<1	<1	nil	<1
PNA	nil	nil	nil	<1
NO_x	16	2	3	21
Combustion-Improving Additives				
Lead	nil	nil	nil	nil
Fuel Contaminants				
SO_x	59	4	nil	63
Ash (Noncombustible Particulate)	72	<1	nil	72

*Data derived from Table II-1.

Clearly, central-station power plants are important emitters of combustible particulates, nitrogen oxides, sulfur oxides, and noncombustible particulates (ash), and they are likely to remain so unless appropriate steps are taken.

The generation of electric power by public utilities is expected to increase from about 1.57 x 10^{12} kWh in 1970 to 2.4 x 10^{12} kWh in 1975, a growth of 53 percent in the 5-year period. Historically, the generation of electric power has about doubled every 10 years. For the future, many estimates call for doubling in 8 years. Most of this power is and will be generated by the combustion of prime fuels. The following tabulation shows the sources of energy for the current pattern of electric-power generation.

Energy Sources for the Generation of Electric Power by Public Utilities (1969)

Fuel	Percentage
Fossil-Fuel-Fired Plants	
Coal	49
Oil	9
Gas	22
Noncombustion Plants (Nuclear, Hydro, Etc.)	20

Little combustion research is now being conducted by boiler manufacturers, public utilities, fuel suppliers, or research laboratories to minimize air pollution resulting from the combustion process itself in large central-station power plants. Central-station power plants traditionally have sought to produce electricity at the lowest possible cost, achieved mainly by engineering advances and by empirically derived developments.

Historical Background of Development

Fuel economy in the best plants has not changed radically since 1950, approximating 8600 Btu per kWh, or an overall thermal efficiency of 40 percent. Conditions in boiler furnaces are about the same as they have been for the past few decades.

Figure III-1 illustrates a typical time-temperature profile in a modern boiler.

The one significant change in generating electricity has been in the increasing size of the boilers. Over the past 25 years, the largest boilers have increased from less than 100 MW capability to more than 1000 MW; units rated at 1300 MV are now on order. Steam pressure has increased from 2400 psi to 3500 psi in 25 years, but steam temperature has not changed appreciably over this time, increasing only from 950 F to 1000 F. Units have been built with pressures up to 5000 psi and temperatures up to 1200 F, but these are exceptions, not the rule. Thus, while the physical size of boiler furnaces has increased tremendously, the temperature of the heat-receiving surfaces, and hence the heat-absorption rate, has not changed significantly.

Although combustion research has aided broadly in the design of large boiler furnaces, generally these units have been improved by small incremental design changes, largely on an empirical basis. There has been little variance in the basic design of boiler furnaces over the last 25 years, and little change is foreseen in the immediate future except for the possible introduction of fluidized-bed combustors.

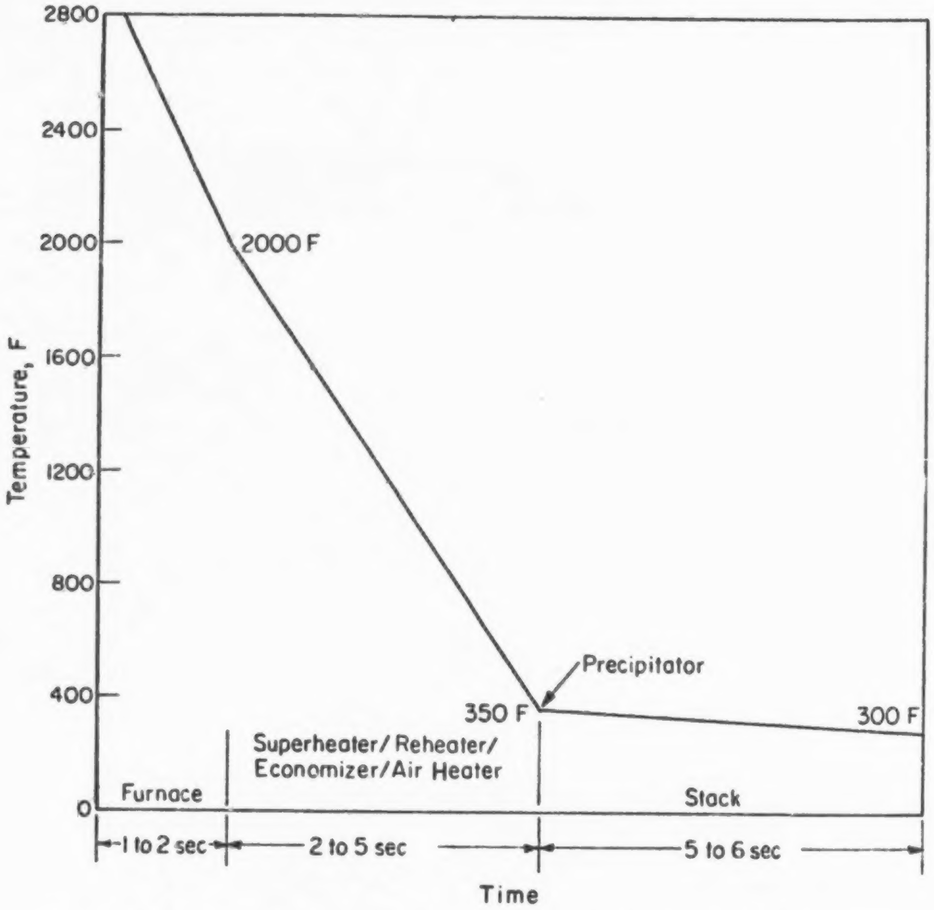

Figure III-1. Time-Temperature Profile in a Typical Large Boiler Furnace

Future Criteria for Design

The economics of power generation may have to be revised radically in light of the present demands for clean air. Minimum costs per kWh of output – the goal of central-station power-plant operators since the industry began – may now have to be replaced by a new criterion of minimum contamination of the atmosphere per kWh generated. In the future, the costs of clean operation may have to be accepted in the same way as the costs of fuel, of maintenance, or of money. With this viewpoint, predictions of the lower limits of emissions from future large boiler furnaces should be based on what will be technically feasibility rather than on cost. At the same time, when a choice is available between alternative schemes, the lower cost one will naturally be selected. The estimates in this chapter of probably attainable levels of pollutants reflect emphasis on feasibility rather than on cost, but without ignoring economics entirely.

The burning of fuels in fluidized beds is discussed in a separate section because of the wide interest in this unique combustion process.

POLLUTANTS OF PRINCIPAL CONCERN

Four classes of pollutants generated by central-station power plants are of most concern:

- Products of incomplete combustion, including fuel emitted as combustible particulate matter, CO, gaseous HC, and PNA
- NO_x
- SO_x
- Fly ash and particulates formed from fuel contaminants and from noncombustible additives.

Products of Incomplete Combustion

Small amounts of unburned fuel are emitted from modern coal-fired boiler furnaces. In most cases, such unburned coal particles are coked, often forming cenospheres* with low bulk density. This devolatilized, unburned coal seldom exceeds 25 percent of the weight of the fly ash. On an efficiency basis, the carbon loss usually will not exceed 0.5 percent of the coal fired.

Droplets of fuel oil will not survive the flame in a boiler furnace, although, if atomization is poor, "sparklers" of larger-than-average oil droplets can be seen beyond the normal flame envelope. When burning residual fuel oil with very low excess air to prevent formation of SO_3 (typically as little as 0.2 percent oxygen in the flue gas), small amounts of CO may be present in the flue gas. Very-low-excess-air operation, although practiced widely in Europe, has not been popular in the United States because of associated control problems.

CO levels in flue gas are usually under 1000 ppm and sometimes as low as 100 ppm. Other substances that may be emitted as partial oxidation products of the fuel are aldehydes and organic acids, and PNA. The organic acids usually are not characterized, although formic acid probably predominates. Polynuclear aromatics, including pyrene, perylene, benzopyrene, anathrene, and coronene have been identified in flue gas from coal-fired units.

Nitrogen Oxides

To attain high combustion efficiency and to use boiler-furnace volume effectively, combustion temperatures frequently reach 3100 F in large central-station units. Such high temperatures are maintained for a short time, perhaps as little as 50 milliseconds in the flame region. The flue gas is then cooled to about 350 F over a period usually ranging up to 5 seconds, as shown in Figure III-1.

Nitrogen in combustion air reacts with oxygen at the peak temperatures to form NO, the amount so produced depending largely on the peak temperature. Nitrogen compounds in the fuel also may contribute to NO_x formation.

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*Cenospheres are microscopic, porous spheres of carbon remaining after partial combustion of a hydrocarbon.

Sulfur Oxides

Natural gas is the only fossil fuel used in power plants that is substantially free of sulfur. Coal contains varying amounts of sulfur as organic sulfur which is part of the coal substance itself, and as pyritic sulfur which exists as discrete particles of FeS_2. On the average, these two forms of sulfur are about equally prevalent in American coals. Some of the pyritic sulfur can be removed by coal preparation, but none of the organic sulfur can be removed without destroying the complex coal substance. Hence, most of the sulfur originally in coal, ranging typically up to 5 percent, enters the furnace and is converted by combustion into sulfur oxides, mostly SO_2. Insignificant amounts of sulfur are captured by slag, bottom ash, and fly ash.

In oil, sulfur occurs as part of the complex mixture of compounds making up petroleum fuels. Residual fuel oil occasionally contains up to 5 percent sulfur. No physical methods will remove such sulfur compounds, but hydrodesulfurization can remove varying amounts of sulfur during refining. Costs of desulfurization are high but are decreasing.

It is axiomatic that, at usual furnace temperatures, changes in combustion have no effect on SO_x emission other, possibly, than shifting the ratio of SO_2 to SO_3, which is usually 100:1. Only under highly reducing conditions, not currently used in steam-power-plant practice, is the sulfur present as H_2S.

Fly Ash and Other Noncombustible Particulates

Coal-fired dry-bottom furnaces capture only a small amount of the ash present, perhaps 20 percent. With slag-tap furnaces, about half the ash forms slag on the furnace walls and on the hearth, and with cyclone furnaces, about 90 percent of the ash forms slag. The remaining ash in each case either is caught as deposits on superheater and reheater elements or in ash hoppers, or is carried out of the boiler as fly ash. A combination of mechanical and electrostatic collectors can usually remove at least 95 percent of this particulate matter from the flue gas, and occasionally as much as 99 percent.

Coal contains 100 to 200 times more ash than fuel oil. Hence, the fly-ash problem is more serious for solid fuels than for liquid fuels. Changes in the combustion system of coal-fired units have little effect on the emission of ash except that slag-tap and cyclone furnaces are more effective than dry-bottom furnaces in converting ash into slag, and therefore in decreasing the dust burden in the flue gas. Generally, the quantity of ash emitted from oil-fired boiler furnaces is insignificant. Nevertheless, even this small amount of ash can cause a problem by forming a visible stack plume.

Two forms of noncombustible additives that contribute to particulate emissions are used in oil-fired boiler furnaces: (1) MgO as a means of controlling external corrosion and (2) metal-based proprietary compounds added as "combustion improvers". Neither type of additive is used in large quantities and their contribution to power-plant emissions is negligible.

EMISSION LEVELS FROM COMBUSTION PROCESSES

Following are discussions of levels of emission with present practice and levels probably attainable with the latest technology.

EMISSION LEVELS WITH PRESENT POWER-PLANT PRACTICE

Products of Incomplete Combustion

Combustible loss when burning pulverized coal depends upon many factors, such as the heat-liberation rate in the furnace, the proximate analysis of the coal (in particular the volatile matter), the particle size of the pulverized coal, and the excess air. In short, the parameters of time, temperature, and turbulence – plus the reactivity of the coal – all influence the fraction of unburned fuel escaping from a large central-station boiler furnace.

Unburned Carbon

At typical operating conditions* the carbon loss can be expected not to exceed 0.1 percent with dry ash removal and about half this for a slag-tap furnace.(1) Table III-2 shows the carbon loss that can be expected when burning coals of different volatile content under various

Table III-2. Unburned Carbon Loss From Pulverized-Coal-Fired Boiler Furnaces(1)

Heat Release Rate, 1000 Btu/ft^3-hr	Volatile[a] Matter in Coal, percent	Coal Smaller Than 200 Mesh, percent	Excess Air, percent	Unburned Carbon, lb/10^6 Btu Input[b] Dry-Bottom Furnaces	Unburned Carbon, lb/10^6 Btu Input[b] Slag Tap Furnaces
20	20	65	10	3	3
20	48	65	10	0.3	0.2
20	48	80	10	0.06	0.03
20	48	80	40	0.03	0.02
40	20	65	10	5	3
40	48	65	10	0.6	0.5
40	48	80	10	0.2	0.2
40	48	80	40	0.06	0.05

(a) Dry, ash-free basis.
(b) Based on 13,100 Btu/lb for coal.

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*For example, a furnace liberation rate of 20,000 Btu per cu ft-hr with 48 percent volatile matter on a dry, ash-free basis, with 80 percent of the coal pulverized to a particle size smaller than 74 microns, and with 10 percent excess air.

conditions. It is evident that the rank of the coal is highly important, with furnace heat-liberation rate and excess air having a significant effect. Both heat-liberation rate and excess air are controllable, and their effects might be enhanced by the results of appropriate combustion R&D. However, the small quantity of unburned carbon leaving the furnace provides little incentive for improvement.

When burning oil, the same general conditions apply except that droplet size is significant rather than particle size, and excess air is less important. One problem encountered with oil-fired furnaces that does not occur with coal-fired units is the emission of "acid smuts", agglomerates of unburned carbon saturated with condensed sulfuric acid. Control measures are available,(2) and acid smuts presently pose no real problem in central-station power plants.

Carbon Monoxide

The level of CO in the flue gas of large boiler furnaces is low. Because CO represents a loss in fuel, it is kept to levels below the detection limits of conventional Orsat gas analyzers, or less than 0.1 percent (1000 ppm). With low-excess-air burners, CO levels, measured by an infrared analyzer, can be used to control the combustion air. The first significant measurable increase in CO is taken as a signal that the oxygen available is inadequate.

Bureau of Mines measurements(3) in a pulverized-coal-fired boiler furnace showed momentary CO peaks of as much as 1000 ppm, but with the usual levels well below 100 ppm. Hangebrauck(4) reported CO levels equivalent to 0.004 to 0.10 lb per 10^6 Btu input for pulverized-coal-fired furnaces. At the 100-ppm level, 0.084 lb of CO is present in flue gas for 10^6 Btu input.

Polynuclear Aromatics

Information on the presence of PNA in the flue gas of central-station power plants has been obtained by the Public Health Service,(5,6) the Bureau of Mines,(3) and Bituminous Coal Research, Inc.(7) No consistent pattern has emerged relating emission levels of PNA and operating conditions in central-station power plants.

The one major factor apparently affecting the output of a typical polynuclear aromatic [benzo(a)pyrene (BaP)] is gross heat input to the furnace. Table III-3 compares the effect of heat input on the amount of benzo(a)pyrene (BaP) emitted for systems ranging from hand-fired to central-station power-plant furnaces burning coal, oil, and gas.

Nitrogen Oxides

The amount of NO_x in flue gases depends largely on the peak temperature reached during combustion, since the cooling rate is high and the rate of decomposition is low. The primary reaction product is NO, with NO_2 formed after the flue gases are cooled.

Figure III-2 illustrates the NO level in eight different central-station boiler plants burning gas and oil in horizontal or tangentially fired furnaces.(8) In these examples, higher NO concentrations occurred with oil firing than with gas by a factor of about 2. Figure III-2 also illustrates that there can be large differences between different units. No firm explanation is available concerning the pronounced influence of the firing method. Obvious possibilities are that the peak temperatures must vary and that the residence times can be appreciably different.

Table III-3. Effect of Gross Heat Input on Emission of Benzo(a)Pyrene(5,6)

Fuel	Gross Heat Input to Furnace, Btu/hr	BaP in Flue Gas, micrograms/10^6 Btu input	
		Maximum	Minimum
Coal	5×10^4	1×10^7	4×10^3
Oil	5×10^4	100	<40
Gas	5×10^4	<20	–
Coal	1×10^7	4×10^3	50
Oil	1×10^7	50	20
Gas	1×10^7	<20	–
Coal	1×10^9	5×10^2	15
Oil	1×10^9	–	–
Gas	1×10^9	–	–

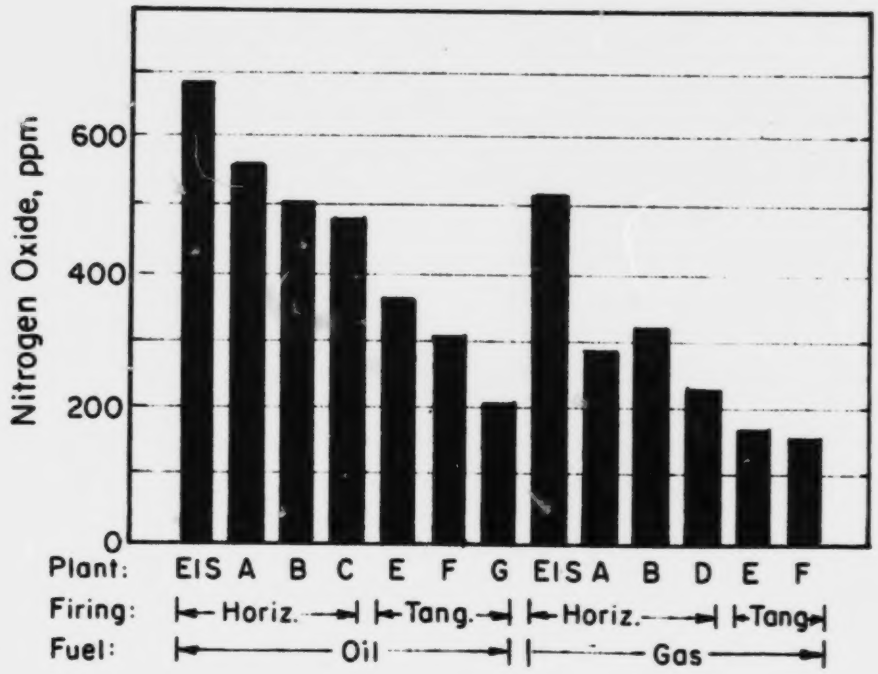

Figure III-2. Comparison of Horizontal and Tangential Firing, Oil and Gas Fuel, Normal Full-Load Operation(8)

Without making major changes, but by varying auxiliary air dampers, NO_x levels have been lowered in some of the units of Figure III-2 by up to 32 percent for oil firing and up to 31 percent for gas firing.(8) By partially delaying air admission, and thus the final complete oxidation of the fuel, peak temperatures and the NO_x concentration are decreased. Despite this success, "two-stage" combustion is not used commonly in everyday practice.

Figure III-3 illustrates experimental work in a small-scale test tunnel and the actual NO levels in the El Segundo Station of the Southern California Edison Company.(9) With 85 percent of the air supplied through the burner in the test tunnel, NO levels were less than a third of those with the total air supplied through the burner. It was found that essentially all formation of NO occurred within a comparatively small zone within a few feet of the burner. Limited recirculation in the test tunnel had little effect on NO formation and humidifying the combustion air did not lower the NO appreciably. The reason for this is not clear, since the flame temperature should have been decreased significantly both by recirculation and by increasing the humidity.

Emission of NO_x from coal-fired boiler furnaces depends at least in part on the way the coal is fired, and on the boiler load. Under full-load conditions, for example, firing pulverized coal through either vertical, corner, or wall burners showed about a 2 to 1 difference in NO_x emission, the NO_x levels after the fly ash collector ranging between 310 and 606 ppm, or 0.55 to 0.95 lb NO_x per 10^6 Btu.(10) With a cyclone furnace, where the temperatures are higher, 1160 ppm or 2.2 lb NO_x per 10^6 Btu was emitted. At part load, the amount of NO_x was

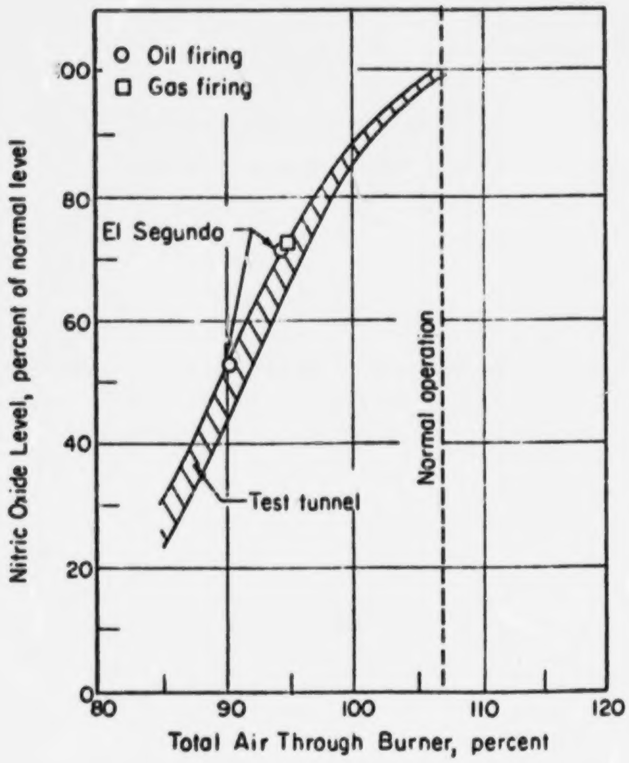

Figure III-3. Comparison of El Segundo and Alliance Test-Tunnel Results During Two-Stage Combustion(9)

appreciably less, ranging between 171 and 453 ppm, or 0.31 to 0.74 lb per 10^6 Btu for pulverized coal, and 784 ppm, or 1.8 lb per 10^6 Btu for cyclone firing. There is an appreciable difference possible between individual units, and there is the further complication of the influence of nitrogenous compounds in the coal. The coals fired here contained from 1.3 to 1.6 percent nitrogen as shown by an ultimate analysis; the exact nitrogen compounds in the coal were not investigated.

According to the extensive NAPCA/Esso study,(11) electric generating plants can be expected to emit 0.76 lb of NO_x per 10^6 Btu input for coal, 0.69 lb for residual fuel oil, and 0.38 lb for natural gas.

Sulfur Oxides

Emission of SO_2 depends almost entirely on the amount of sulfur in the fuel. A possible exception is with coals containing appreciable amounts of CaO in the ash, as do some Illinois coals and a few of the lower-rank coals. In such cases, as much as a fourth of the sulfur may be retained in the ash as $CaSO_4$. It can be assumed generally that 95 percent or more of the sulfur in the fuel will be evolved as SO_x if the fuel is burned in conventional furnaces.

With the coals commonly burned today, the SO_2 in flue gas ranges from about 800 ppm to 4000 ppm. Table III-4 lists SO_2 emissions for typical sulfur levels in American coals. It also shows the SO_3 emissions, assuming that SO_3 is one percent of the SO_2. SO_3 in flue gas, which even in very low concentrations can produce a visible plume from the stack, results from reactions in the flame where oxygen atoms oxidize SO_2 to SO_3. Figure III-4 shows the change in flame-produced SO_3 under noncatalytic conditions as excess air is varied.(12)

The oxidation of SO_2 to SO_3 by catalytically active surfaces contributes little or nothing to the SO_3 in flue gas; such SO_3 commonly reacts with the surface or is adsorbed on fly ash. The amount of SO_3 formed this way can vary widely; generally it amounts to less than 5 percent of the total sulfur in the flue gas.

Table III-4. Sulfur Oxides in Flue Gas From Coal Firing[a]

Sulfur in Coal, percent	SO_2 in Flue Gas, ppm[b]	SO_2, lb/10^6 Btu Input[c]	SO_3 in Flue Gas, ppm[d]	SO_3, lb/10^6 Btu Input[d]
1	800	1.53	8	0.019
2	1600	3.06	16	0.038
3	2400	4.59	24	0.057
4	3200	6.11	32	0.076
5	4000	7.64	40	0.095

(a) Assuming no capture of SO_2 by coal ash.
(b) Based on 140 ft^3 wet flue gas/lb coal at 32 F and 1 atm.
(c) Based on 13,100 Btu/lb coal.
(d) Based on SO_3 in flue gas being 1 percent of the SO_2.

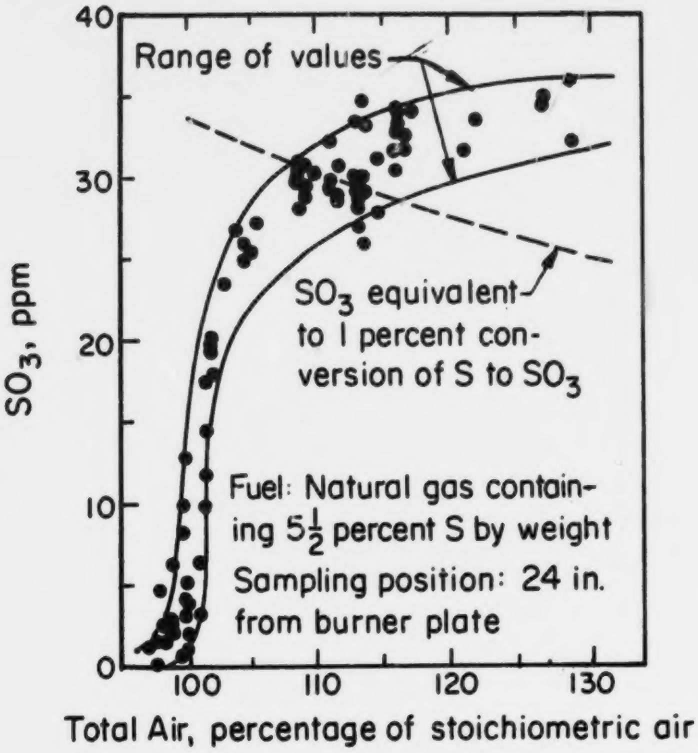

Figure III-4. Effect of Excess Air on Formation of SO_3[12]

Table III-5. Fly Ash in Flue Gas

Coal: 10 percent ash; 13,100 Btu/lb

Dusting Loading as Percentage of Ash in Coal Fired	Ash Suspended in Flue Gas lb/kWh Output[a]	Ash Suspended in Flue Gas lb/10^6 Btu Input
10 (typical cyclone burner)	0.0065	0.76
25	0.016	1.90
50 (typical slag-tap furnace)	0.033	3.80
80 (typical dry-bottom furnace)	0.052	6.08
100	0.065	7.60

(a) Based on 40 percent overall thermal efficiency.

Fly Ash and Other Noncombustible Particulates

The quantity of fly ash emitted by modern boiler furnaces depends on the fusion characteristics of the ash, the furnace design, and the time-temperature-turbulence conditions in the furnace during combustion.

Table III-5 lists calculated quantities of solid particulates suspended in the flue gas for varying levels of dust loading. Part of the fly ash settles and is caught in ash hoppers and mechanical collectors as the flue gas moves through the boiler. This fraction varies widely, and only the larger particles of ash are removed in this way. Electrostatic precipitators are commonly used to capture smaller particles, and there has been some experimental use of bag filters to remove the smallest ash fragments.

EMISSION LEVELS FOR POWER PLANTS PROBABLY ATTAINABLE WITH LATEST TECHNOLOGY

Products of Incomplete Combustion

There appears to be no inherent technical reason why the amount of carbon, CO, and PNA from conventional large boiler furnaces should not be held at the lowest levels that have been observed in such furnaces. As an example, for pulverized-coal-fired boilers these levels are:

Combustible particulate	0.05 lb per 10^6 Btu input
CO	0.0004 lb per 10^6 Btu (5 ppm)
PNA	5.5 lb per 10^{12} Btu.

The high-temperature and long-residence-time requirements to reach these levels do not appear to be so great as to conflict with the requirements for low NO_x. Smaller furnaces, to match the emission levels of larger units, might require such changes as higher rates of heat release and the use of fuels that react more rapidly. However, the trend of the public utilities is to larger and larger furnaces.

Making further improvements in performance will require a more detailed understanding of the effect of time, temperature, and turbulence on the burnout of the products of incomplete combustion, plus a translation of this understanding to changes in design and operation.

Nitrogen Oxides

The concentration of NO formed during combustion is controlled by the peak temperature, the availability of nitrogen, and – according to the usually accepted reaction mechanism – the concentration of oxygen atoms.

As all practical central-station combustion devices must use air as the oxidant, there is little possibility of reducing the availability of nitrogen. Most attempts at reducing the concentration of NO have centered on reducing the peak combustion temperature. Such attempts include the use of two-stage combustion, with heat extraction, and cooled-flue-gas recirculation.

The possibility of reducing the O-atom concentration has not been widely considered. Operation near stoichiometric fuel-air ratio, which would be expected to reduce the O_2 and O levels, can result in high NO levels if the temperature is increased. However, it should be noted that a reduction in O-atom levels would be expected in the first stage of a two-stage burning process and that this may contribute to the observed reduction in NO.

Experiments on two-stage combustion in boiler furnaces(9) have demonstrated a reduction in NO_x levels of about 50 percent, and in an experimental combustor, a reduction of about 70 percent. Extrapolation of these results suggests that a well-engineered two-stage combustion system might reduce the NO_x levels to about 10 percent of the current levels, or 0.04 - 0.07 lb per 10^6 Btu for gas- and oil-fired boilers.

For coal-fired units, the best performance demonstrated in an actual central-station plant appears to be an emission of about 0.5 - 0.6 lb NO_x per 10^6 Btu from a conventional pulverized-coal-fired unit. However, in experiments in a small furnace simulating a central-station boiler furnace, changes in excess air level and control of air admission locations made possible NO_x reductions of perhaps 60 percent (from 550 ppm to 210 ppm in the experimental furnace).(13) If these results could be duplicated in a full-scale boiler furnace, emission levels of 0.2 - 0.4 lb 10^6 Btu would result.

Sulfur Oxides

If downstream control measures and fuel selection are excluded, there is no current or near-future technology available to control SO_x emissions from central-station power plants, with the exception of fluidized-bed combustors using limestone or dolomite as the inert bed material. Emissions are thus dependent on the sulfur content of the fuel and are as previously described in Table III-4.

Fly Ash and Other Noncombustible Particulates

Emissions of fly ash and other noncombustible particulates are currently controlled by downstream methods, and no control measures are known which could eliminate the need for such downstream controls, although, as pointed out previously, changes in the firing method can reduce the dust burden on the collectors.

An important aspect of fly-ash control is that when the SO_3 level in the flue gas is reduced, conventional electrostatic collectors become less efficient.

PROMISING NEW COMBUSTION SYSTEMS

Two unconventional approaches to combustion for central-station power plants are receiving new attention, namely fluidized-bed combustion and gasification of fuels for advanced power cycles. These concepts are discussed in this section.

CONTROL OF EMISSIONS WITH FLUIDIZED-BED COMBUSTION

Burning crushed coal in a fluidized bed of limestone could have considerable merit for reducing air pollution. The residence time can be made long, and the fuel-bed temperature limited to perhaps 1800 F. Calcined limestone should be effective in capturing SO_2 and SO_3 since $CaSO_4$ is stable at this temperature. Further, since one of the features of a fluidized bed is temperature uniformity, there should be no localized high-temperature zones, and the formation of NO_x would be largely avoided. Particulate emission might be high, requiring an electrostatic precipitator to prevent excessive emission of fly ash from the stack.(14)

Status of Fluidized-Bed Combustion

Most investigations of fluidized-bed combustors have been done on a laboratory scale, and most of the projections for large-scale systems for central-station power plants must be based on these limited data, including burning rates, carryover, heat transfer, SO_2 capture, and the like. However, sophisticated engineering analyses are being done now to lead to concepts for eventual trial on a large scale.

United States

In the United States, Pope, Evans and Robbins(15) have investigated fluidized-bed combustion experimentally most extensively but their efforts have been directed toward industrial boilers with an output up to about 350,000 lb per hr of steam. Such preassembled boiler furnaces with maximum shipping dimensions of 12 ft wide, 16 ft high, and 60 ft long would provide this rating. Ten or more of these "modules" might be assembled further into a large boiler furnace with an output of 3 to 5 10^6 lb per hr of steam.

The modular fluidized-bed boiler concept of Pope, Evans and Robbins is based on BCURA's projection of a heat release of a 10^6 Btu per sq ft-hr for the fuel bed, equivalent to burning 76 lb per hr of a typical bituminous coal. On establishing the design parameters of the Fluidized Bed Module (FBM)(15) at this burning rate, it was found by these investigators that imbedded heat-transfer surfaces were undesirable. Excessive cooling of the bed could lead to excessive carbon losses through carryover, even with a secondary, lower-velocity carbon-recovery fluidized bed operating at 2000 F. Nevertheless, Pope, Evans and Robbins are enthusiastic about the modular concept as the proper approach to large utility-type boilers. Their projected heat balance for a 50-MW fluidized-bed utility boiler shows a net thermal absorption of 91.8 percent and a carbon loss of 2 percent.

The U. S. Bureau of Mines(15) has investigated the burning of coal in a fluidized-bed combustor as a means of reducing the emission of pollutants. Their goals are to evaluate the suitability of different coals; to study erosion, corrosion, and deposition on heat-transfer surfaces; and to determine heat-transfer characteristics in fluidized beds. Preliminary burning tests have been made using alumina as the inert bed material. Boiler-tube investigations, to be made in an 18-inch-diameter combustor, using eight types of alloys (ranging from mild steel to TP 316 alloy containing 18Cr, 14Ni, and 3Mo) were planned for late in 1970. Based on tests of only 100-hr duration, there is some question that enough damage will occur under non-accelerated conditions to permit meaningful extrapolations of metal wastage for different alloys over the nominal life of a fluidized-bed combustor.

A wide variety of concepts are being evaluated by Westinghouse,(15) mostly stressing a pressurized system at 10 atmospheres to operate in conjunction with a gas-turbine expander. In their preliminary design calculations for a unit with a rating of 600 MW, regenerated lime would be used to capture 95 percent of the SO_2 in the flue gas. This would require large amounts of lime in the bed – about 8 times stoichiometric based on SO_2 – which mainly would affect the costs of handling and regeneration. Details of the final system are still being developed. For the present, a modular design based on a unit 12 ft by 16 ft by 40 ft is being considered to permit shop fabrication. This unit would have a fluidized bed area of 50 to 60 sq ft. The number of these units required, the configuration in which they are stacked, and details of the handling of solids and gases have not been established as yet. Projected cost for the pressurized power plant is $156 per kW, based on a boiler efficiency of 89 percent and allowing $40 per kW for the fluidized-bed system. The major design details yet to be established concern the arrangement of heat-transfer surfaces; the location and physical layout of evaporator, superheater, reheater, and economizer sections; and the provision of baffles and gas deflectors to minimize carryover.

Preliminary layouts proposed by Foster Wheeler(15) for Westinghouse call for tall cylindrical boiler furnaces with annular or rectangular beds to make maximum use of the space within the pressurized shell. Annular beds are preferred; coal would be introduced tangentially at a number of points on the outer periphery of the beds. Such a concept permits stacking evaporator, superheat, and reheat sections of the boiler in one continuous shell, simplifying gas handling. Comparison between pulverized-coal-fired boiler furnaces and the proposed fluidized-bed system with a gas turbine show a markedly smaller combustor for the fluidized system, with material costs only 18 to 19 percent that of conventional units. Final concepts are still being developed.

Consideration is being given(15) to the Ignifluid process for two 300 MW units at the proposed Nanticoke Station of UGI (The United Gas Improvement Co.) to burn Pennsylvania anthracite culm. Tests in France burning this Pennsylvania anthracite in an Ignifluid unit suggest that a burning rate of 130 lb per sq ft-hr can be achieved, but carbon in the resulting ash from the anthracite culm in these tests was 17 to 20 percent. Hence the proposed boiler furnaces will require post-combustion units to decrease the carbon loss to 10 percent of the ash. The exact status of these two proposed units is not clear.

France

The "Ignifluid" process developed in France has been intended for industrial rather than for utility applications. Proposals have been made to build 250-MW power plants in Europe with twin Ignifluid boilers, but the present status of those proposals is unknown. Interest in the United States by UGI may lead to large-scale units here before they are available in Europe.

Germany

Lurgi(24) has developed a fluidized-bed combustion system to dispose of refinery wastes in Germany, but the fuels are sufficiently different and the scale of the combustor is small enough that the design may not be easily adaptable to large central-station power plants. Data from that development, nevertheless, should be helpful.

Czechoslovakia

A large effort on fluidized beds has been going on in Czechoslovakia, mainly as a way of burning coals containing more than 50 percent ash. The fluidized combustor is to act as a gas producer, not a steam generator, by burning the coal with about one-third stoichiometric air. This gas then is to pass to a conventional boiler where the remaining air will be provided. Plans were being made in 1969 to build a 33-MW demonstration unit with a 10-ft diameter combustor.

England

The National Coal Board (NCB) in England has been particularly active in fluidized-bed combustion, both at their laboratories in Stoke Orchard and at the BCURA Industrial Laboratories in Leatherhead. Their work stresses economics. Because a fluidized bed can maintain a heat-transfer coefficient of 50 to 100 Btu per sq ft-hr-F at a bed temperature of 1500 F, at least a four-fold reduction is expected in the capital costs of a boiler, superheater, and reheater. Further, at this low combustion temperature, plant availability should be improved because of freedom from external corrosion and deposits. Taking into account increased costs for compressing the fluidizing air and distributing it to the combustion zone should still lead to an expected net savings of 10 percent in the overall costs of a 500-MW unit, according to early estimates by NCB.

In recent tests(24) of British coals by the NCB at a fluidizing velocity of 3 fps, it was found *on the average* that a Ca/S ratio of 1 would remove 48 percent of the SO_2 from flue gas; a Ca/S ratio of 2 would remove 75 percent; and a Ca/S ratio of 3 would remove 94 percent.

Conceptual designs were begun by NCB in 1968 of a 600-MW and a 120-MW power plant, based on a fluidizing velocity of 3 fps and a bed area of 38 sq ft per MW. For the 660-MW station, 25,000 sq ft of bed would be required, distributed as 15 beds, each 80 ft by 20 ft in area, with a bed depth of 2 ft. Tubular heat-receiving surfaces would be in two or three horizontal layers immersed in the fluidized bed. The total depth of the unit is not described, nor is the arrangement of gas-offtake flues, economizers, air heaters, and the like. Other details have not been established, such as control and distribution of coal to the beds and within each 1600-sq ft bed; the type of wall and roof construction, whether water-wall or refractory; the method of start-up; or the means of accommodating rapid large swings in load.

The work at the BCURA Industrial Laboratories has been along two main lines: atmospheric-pressure units for large utility boilers as well as industrial steam generators, and a 5-atmosphere pressurized combustor for an advanced cycle involving a gas turbine. Experimental rigs for both concepts have been built at Leatherhead.

The combined cycle being considered at BCURA would use a fluid-bed combustor operating at 87 psi to generate steam, with the hot flue gas expanding through a gas turbine.(16)

Their pilot-scale rig, built inside the pressure shell used earlier at BCURA in studying gasification, provides a rectangular fluidized bed with an area of 8 sq ft, in which it is expected that 1000 lb per hr of coal can be burned at temperatures up to 1500 F. At this moderate level, the coal ash will not sinter and the formation of NO should be low.

The earliest significant experimental results at BCURA show that coal crushed to -1/16 in. can be burned in a fluidized bed of coal ash at air velocities ranging from about 2 to 14 fps, and at bed temperatures of 1500 F without sintering the coal ash. Heat-transfer coefficients attained have been between 40 and 100 Btu per sq ft-hr-F. CO in the flue gas was high at a stoichiometric air/fuel ratio, sometimes reaching 1 percent. In this early work at BCURA, 20 percent excess air lowered CO to 0.5 percent, and 50 percent excess air was required to decrease the CO to less than 0.2 percent. Major fuel losses, however have been in elutriation of unburned coal from the bed, as was also the case for the Pope, Evans and Robbins fluidized combustor. Without recycling cyclone-captured particles, this loss has been as high as 25 percent. With recycling, carbon loss has been decreased, but it may reach 10 percent at high fluidizing velocities.

Australia

In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO) is investigating combustion in fluidized beds with considerable emphasis on heat transfer.(17) Early tests were made in a 9-in.-diameter bed of fluidized sand at temperatures in the range 750 F to 1850 F. The maximum rate of heat release was 124,000 Btu per cu ft-hr of combustion chamber, with virtually complete combustion at only 2 percent excess air. Maximum heat-transfer coefficient was 50 Btu per sq ft-hr-F, about half the maximum reported by others. This coefficient decreased as the temperature in the bed increased, explained by CSIRO as the result of increased voids in the bed at higher gas-flow rates. Although operating a fluidized combustor at increased pressure should increase output as far as *heat release* is concerned, as well as improve the quality of fluidization and offset the effect on gas density of expansion of gas in a hot fuel bed, any possible benefits of pressure may be lessened because the overriding factor influencing the capacity of the system is *heat transfer* and not heat release.(18)

Present plans by CSIRO include studying the behavior of inorganic matter in Australian coals in a 3-stage experimental combustor 1 ft square and 12 ft high. The main bed will have a depth variable between 6 and 36 in., and the two successive beds each will be up to 12 in. deep.

Burning Rates in Fluidized-Bed Combustion

There is no general agreement as yet on the burning rate most desirable in a fluidized-bed combustor. This rate depends on many factors, involving highest permissible fuel-bed temperature, fuel reactivity, and carryover. In the interests of low initial capital investment, high burning rates are wanted, but if this in turn leads to excessive carryover, or to sintering of ash, then lower burning rates may have to be accepted.

In the Czechoslovakian combustor burning a coal with a calorific value probably not higher than 7000 Btu per lb, the firing rate necessary to generate 33 MW at 40 percent overall thermal efficiency will be 40,000 lb per hr of coal. For the proposed 10-ft-diameter fluidized combustor, the burning rate of coal would have to be 510 lb per sq ft-hr.

For the NCB estimate of 38 sq ft per MW, assuming a coal with 12,000 Btu per lb, the burning rate will be 700 lb per sq ft-hr. With the BCURA pressurized combustor at roughly 6 atmospheres, the burning rate will be 125 lb per sq ft-hr. As noted earlier, the Ignifluid tests burning anthracite culm were at 130 lb per sq ft-hr. The burning rate in the proposed Westinghouse 10-atmosphere combustor might be estimated from the stated volumes of the fuel beds for the evaporator, superheat, and reheat sections, but other factors related to the depth of the beds have not been established as yet.

Fluidizing velocity affects performance in that high air velocity requires larger fuel particles to limit carryover losses, but these larger particles lead to a lower heat-transfer coefficient.(15) Hence there is a tendency to use moderate air velocities, both from the standpoint of heat transfer and carryover, but this means that the rating of the unit may be less than if higher velocities were chosen. It is apparent, then, that the choice of fluidizing velocity is an engineering compromise to achieve high throughput, a reasonable overall cycle efficiency, and low capital costs and operating charges.

Experimental combustors have operated at much lower rates. A 2-sq ft combustor operated by BCURA(19) is reported to burn coal at 500 lb per hr or 160 lb per sq ft-hr. The small BCURA combustor(14) had a maximum heat input of 3.15 MW per sq m, equivalent to 10^6 Btu per sq ft-hr, or to 83 lb per hr of coal. The much larger beds operated by Pope, Evans and Robbins also were based on a heat input of 10^6 Btu per sq ft-hr(14), again equivalent to 83 lb per hr of coal. Tests by the Bureau of Mines(14) in a 2-ft-diameter bed burning anthracite showed a burning rate of only 9 to 17 lb per sq ft-hr in a 3-ft-deep bed.

In the Australian work, the three-stage experimental combustor has been designed and is being constructed for heat-release rates varying between 20,000 and 200,000 Btu per cu ft-hr, or 200,000 to 2,000,000 Btu per sq ft-hr. For a 10,000-Btu coal, this is equivalent to 20 to 200 lb per sq ft-hr.

The large discrepancy between experimental results and expected performance can be based in part on the scale of the systems. It may indicate, too, that problems can be expected in operating central-station combustors at heat input rates three to five times greater than have been achieved in small combustors. For the present, it appears that burning rates approaching 150 lb per sq ft-hr of coal may be practical in large combustors.

Emission Data from Fluidized-Bed Experiments

Only a few data are available as yet on the emission of various pollutants from fluidized beds. Brief tests made in England at the BCURA Industrial Laboratories of the National Coal Board showed that chlorine was not retained in conventional beds of fluidized coal ash, and that with coals containing 20 and 35 percent ash of unspecified composition, only 5 to 10 percent of the sulfur was retained in the solids – about the same as would be expected with a chain-grate stoker. At 1600 F, the NO_x output was 400 to 450 ppm, somewhat higher than should be obtained at this temperature, suggesting that nitrogenous compounds in the coal might have been responsible.

In an unpublished report on work at BCURA on the reaction between limestones and SO_2 in fluidized beds(15), which also effectively summarized the state of the art in the United States, similar conclusions were reached as have been drawn from studies of limestone for the dry-injection processes. These conclusions are:

1. Internal surface area of limestones is increased greatly by calcination
2. An impermeable shell of $CaSO_4$ slows down further reaction with SO_x
3. The $CaSO_4$ shell has little effect in some dolomites
4. Fine grinding minimizes the shell effect, with a particle size of a few microns being optimal
5. Reaction rate increases with temperature for limestones but for dolomites is temperature independent between 1300 F and 1650 F
6. CO_2 in the flue gas suppresses the calcination of limestones under pressure but has little effect on dolomite.

These experimental runs were made in a fluidized bed 1.6 in. in diameter, but the report also describes other tests in a fluidized bed 2 ft in diameter and 2 ft deep, where 40 percent of the SO_2 was captured with limestone and 60 percent with another.

Tests in England by the National Coal Board (NCB) in a 6-in.-diameter fluidized bed burning two English coals and one American coal are summarized in Figure III-5.(20) The limestone used contained 99 percent $CaCO_3$. The fluidized fuel bed in each test was 2 ft deep and the gas velocity was 2 ft per second, for an average gas residence time of 1 second. Excess air was 10 to 20 percent, and the fuel-bed temperature was 1470 F.

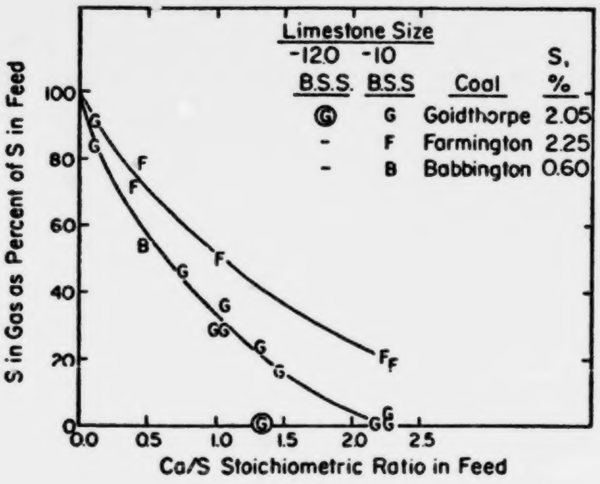

Figure III-5. Retention of Sulfur in Fluidized-Bed Tests by National Coal Board(20)

Capture of SO_2 was affected appreciably by the size of the limestone, the smaller stone being more effective, based on a single test with Coal G. There was an unexplained difference in sulfur retention between Coal F and Coals G and B. However, under these test conditions, it is evident that a stoichiometric ratio of CaO to S resulted in the capture of one-half to two-thirds of the sulfur originally present in the fuel for limestone crushed to -10 B.S.S. Based on the observed effect of particle size, it was concluded by NCB that excess lime was present in the interior of the particles.

A computer program has been written at Argonne(21) to calculate the extent of SO_2 removal in a fluidized bed by a limestone and a dolomite as a function of bed height, superficial gas velocity, particle size, and stoichiometry. A recent paper reported on experimental work at Argonne(22) involving studies in a small laboratory fluidized bed with limestone present to capture SO_2. Factors investigated include gas velocity, the size of the limestone particles, the influence of temperature, and the stoichiometric ratio of Ca to S. These experimental measurements, still in progress, show that about 40 percent of the SO_2 is captured when the Ca/S ratio is one, and that the amount of SO_2 removed increases as the surplus of lime increases. At a stoichiometric ratio of 2, from 60 to 70 percent of the SO_2 is removed; a ratio of 3 is necessary to capture 90 percent of the SO_2. The influence of temperature in the range of 1550 F to 1650 F is negligible. Smaller particles of limestone favor the capture of SO_2, but the minimum size is established by carry-over in the air stream. Gas velocity has an appreciable influence, with about a sixth more SO_2 being removed at 3 ft per second than at 9 ft per second, undoubtedly because of the longer residence time.

Appraisal of Fluidized-Bed Combustion for Power Plants

Translation of all these data in terms of large-scale performance is difficult. The only possible conclusion is that a surplus of limestone above the stoichiometric ratio will have to be added with coal to obtain nearly complete removal of SO_2. This unreacted lime will remain with the ash from the coal and the converted $CaSO_4$ removed from the fluidized bed. Fluidized combustors appear superior in capturing SO_2 to the dry injection of limestone into pulverized-coal-fired boiler furnaces, but the extent of the improvement is not clear as yet. Removal of 80 percent or more of the SO_2 from a flue-gas stream will require large amounts of limestone, probably up to 3 times stoichiometric in some cases, leading to consideration of regenerating the lime as noted by Westinghouse.(15)

Experimental work is continuing by many investigators, largely with APCO support. Important programs are being conducted by Consolidation Coal Company,(23,24) by Westinghouse,(25) and by Pope, Evans and Robbins.(26) Engineering studies now being conducted are bringing experienced power-plant designers into the field to contribute their experience and practical viewpoint.

Fluidized-bed combustors in large central-station power plants will be quite different from today's huge boiler furnaces. Modular design almost certainly will be stressed, but the size and the geometry of fluidized-bed combustors are still unsettled. It is fairly certain that such combustors will be appreciably more effective than other limestone-injection systems in utilizing limestone for SO_x capture when 80 to 90 percent of the SO_x must be removed. They should lead to lower NO_x levels because of the controlled low temperature in the combustor, although this has not been confirmed as yet experimentally. Fluidized-bed combustors will pose problems in particulate emission, probably requiring elaborate reinjection systems to handle carry-over of unburned combustibles. Finally, they may be best adaptable to base-load operation.

It is too soon to compare the overall effectiveness of fluidized-bed combustors with the limestone-slurry scrubbing systems of so much interest presently to the utilities. Both schemes have merit, but both also have disadvantages that will affect their final wide-scale acceptance.

ADVANCED POWER CYCLES

Concepts other than those used presently in central-station power plants undoubtedly will be developed over the next 30 years to convert the energy in fuels into electricity. Magnetohydrodynamics and fuel cells offer most promise of the so-called direct-energy-conversion processes, but both have serious shortcomings. More attractive at present are advanced power cycles wherein two or more energy-extraction systems are combined in a single power plant.

Typical of such systems is the burning of a gaseous fuel in a pressurized boiler furnace followed by expansion of the hot products of combustion through a gas turbine. The gaseous fuel could be natural gas, but a more likely fuel is a hot sulfur-free producer gas made from coal, or a fuel gas produced from residual fuel oil. A suitable gasification scheme including a hot gas-desulfurizing step is required. In addition to a higher overall thermal efficiency, which can be expected to exceed 50 percent, such cycles have the great advantage of essentially complete removal of sulfur and particulates from the exhaust gas. Formation of NO_X might also be less since all the nitrogen compounds in the original coal would have been destroyed during gasification and peak combustion temperatures might be lowered.

Many types of advanced power cycles can be devised, including those in which volatile matter in the coal is distilled off and only the residual char is burned in the power plant. Such systems have been investigated for many years, but without the present-day incentive of emission control. The need for "clean" power is renewing that interest.(27)

Advanced power cycles need to be investigated intensively, not only for their increased thermal efficiency, but because power plants based on such cycles can potentially emit substantially less pollutants than current plants.

GAPS IN NEEDED COMBUSTION R&D TO REDUCE POWER-PLANT EMISSIONS

Operation of large central-station boiler furnaces has become relatively routine, despite the great complexity of today's installations. Similarly, furnace design has settled into a few recognizable patterns, with the three major boiler manufacturers each favoring design concepts that they originated. Such concepts as the cyclone furnace and the corner-fired furnace were developed through long and diligent engineering studies. Combustion "research" was involved only to the extent that it provided a general understanding of the combustion process.

This can be illustrated by the continuous reference to "time, temperature, and turbulence" in comments concerning conditions needed in boiler furnaces. But these terms are used in the qualitative rather than the quantitative sense. The designer provides as much time as possible for combustion within the limits of furnace volume established by construction costs and heat-transfer rates. Temperatures during combustion are established by slagging, external corrosion, and heat-transfer problems. Turbulence is made as great as possible commensurate with reasonable expenditures for fan horsepower. The furnace is more than a combustor; it also absorbs about half of the total heat released, and so its configuration is as much determined by heat absorption as it is by combustion.

So far as the furnace designer is concerned, there have been no gaps in combustion research. He has succeeded admirably with the information available to him in the sense that the market has accepted his product. But he is now being forced to recognize that there are serious gaps when air-pollution-control problems are considered. For example, because the time-temperature history of particles in boiler furnaces is not known, it is not possible to define the environment around a particle of injected limestone. Similarly, little is known about temperature patterns, and even less is known about the influence of such variables as heat transfer, burner design and location, fuel residence time, and reaction kinetics.

The understanding of combustion needed to build a large boiler furnace that meets with market success is not sufficient for control of air pollution. Far more detailed knowledge in many areas will be necessary. In the following discussions a number of major gaps in knowledge about the combustion process in central-station power plants are described and some possibilities for filling these gaps are pointed out.

Two-Stage Combustion

As discussed previously, two-stage combustion has been investigated as a method of controlling NO_X emissions, and has even been demonstrated in a crude way in gas- and oil-fired central-station plants. Further work to achieve an engineering optimization of the process is still required.

Two-stage combustion is not generally regarded as applicable to coal firing, although the earliest downfired furnaces for pulverized coal operated somewhat in this fashion. Also, the work reported by Bienstock(13) can be considered as an approach to two-stage combustion of coal. Thus, the possibility of applying two-stage combustion in coal-fired plants should not be ignored.

Recirculation

The peak temperature in a combustor can be controlled by recirculating cooled flue gas to the combustor inlet, and this offers a means of controlling NO_X emissions. Demonstrations of flue-gas recirculation in central-station power plants and engineering studies to optimize the quantity, temperature, and point of injection of the recirculated gases are needed.

Improved Combustion and Heat Extraction

Emissions of NO_x and products of incomplete combustion might both be better controlled if current understandings of combustion and heat transfer were applied to the design of large boiler furnaces. The concept of a well-mixed zone followed by a plug-flow zone has been shown to be the optimum combustion process in terms of combustion efficiency, and hence would promise to minimize emissions of products of incomplete combustion. A combustion system based on this concept may also be adaptable to good control of heat extraction and thus of the peak flame temperature. Emissions of NO_x might thereby be controlled.

Gasification

Gasification of coal or residual fuel oil can be considered as a type of multistage combustion, where the first stage, the gasifier, is operated fuel rich. Under such conditions, the sulfur in the fuel is released as H_2S which can be removed from the hot gas. Such schemes have been proposed in the past, and Babcock & Wilcox is currently studying one variation where the ash-and-sulfur-free gas is burned in a combined boiler-and-gas-turbine cycle.

Development of the gasifier is an important feature of this process, in addition to the several noncombustion problems. In addition to controlling the emission of SO_x, the multistage feature may contribute to the reduction of NO_x emissions.

Fluidized-Bed Combustion

The combustion of coal in a fluidized bed of limestone has been shown to be a promising method of controlling SO_x emissions. Several combustion problems are involved in this not-well-understood process. These problems include achieving efficient combustion at low levels of excess air, control, and the minimization of fuel carry-over. Satisfactory solutions of these problems are needed. (As in all application areas, only R&D concerned with combustion problems per se is included in the 5-Year Plan.)

Ash Capture

Cyclone furnaces presently capture 90 percent of the ash in coal as molten slag, and slap-tap furnaces capture about 50 percent of the ash. It is not unreasonable to expect that higher captures could be achieved if that were the objective of a comprehensive R&D program. If 99 percent capture were achieved, the emission of particulate matter would be lowered to about 0.08 lb per 10^6 Btu.

Fly-Ash Agglomeration

Ash particles could be much more easily removed from the combustion gases if agglomeration of the fly ash particles could be promoted. In order to adhere, the particles must be "sticky", which implies some lower temperature limit at which agglomeration can occur. High turbulence or pulsating flows may promote agglomeration of the sticky particles.

Ash Fluxing

Slag-tap furnaces are restricted by ash fusibility with respect to the coals they can burn. Fluxing with limestone and mill scale or iron ore can reduce the viscosity of coal-ash slags to almost any desired range. In addition to the possibility of extending the use of slagging furnaces and possibly increasing their ash capture, fluxing would permit the use of low-sulfur coals (which typically have high ash-fusion temperatures) in existing slagging furnaces.

Modification of Fly-Ash Resistivity

Electrostatic precipitators fall in efficiency when the electrical resistivity of the ash particles exceeds about 2×10^{10} ohm-centimeters. Normally SO_3 present in the flue gas from high-sulfur coals condenses on fly-ash particles, forming an adsorbed layer of sulfates that lowers the electrical resistivity. With low-sulfur coals, this layer does not form, and ash resistivity can be too high for effective precipitator action. The only known corrective actions are to operate the precipitator at higher temperatures, say 800 F, where the electrical resistivity of the ash is lower, or to make the precipitator much larger.

To achieve satisfactory ash resistivity, it may be possible to induce changes in the surface of the ash particles by modifying the combustion process or by using some as-yet-undisclosed additive compatible with other requirements.

SUMMARY OF CURRENT AND RELEVANT COMBUSTION R&D

Large central-station boiler furnaces have been developed to their present status mainly by gradual engineering improvements; comparatively little of what is generally termed "combustion research" has been involved in these advances.

The current R&D activities identified during the course of this study are listed in Table III-6.

Table III-6. Current Combustion R&D – Central-Station Power Plants

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
III-a	Systems study of nitrogen oxides control methods	NAPCA-DPCE CPA 22-68-55	Esso Res. & Engr. Co. Linden, New Jersey	Dr. W. Bartok	Define the nature and extent of NO_x emissions in U.S. and recommend 5-year R&D program for control	389,307 (Total)
III-b	Selected R&D of nitrogen oxides control methods for stationary sources	NAPCA-DPCE CPA 70-90	Esso Res. & Engr. Co. Linden, New Jersey	–	Collect additional data on NO_x emissions and investigate the application of control methods on selected sources	363,025 (FY '70)
III-c	Model for NO_x formation in stationary combustion processes	NAPCA-DPCE CPA 22-69-44 Task No. 3	Mass. Inst. Tech. Cambridge, Mass.	H. C. Hottel G. C. Williams A. F. Sarofin	Develop models for the formation of NO_x in furnaces, determine parameters which influence emission levels, and recommend control methods	28,000 (FY '69)
III-d	Reducing emission of sulfur and nitrogen oxides by using fluidized combustion of coal	NAPCA CPA 70-97	National Coal Board Great Britain	–	Investigate the potential of fluidized-bed combustion of coal for reducing SO_x and NO_x emissions	300,000 (FY '70)
III-e	Fluidized-bed combustion studies of various coals	NAPCA-DPCE Interagency transfer	Bureau of Mines Coal Res. Center Morgantown, Pa.	–	Assess feasibility and commercial potential of various coals for firing in fluidized-bed combustors	–
III-f	Reduction of atmospheric pollution by application of fluidized-bed combustion	NAPCA-DPCE Interagency transfer	Argonne Nat'l Lab. Argonne, Ill.	A. A. Jonke	Examine feasibility and prospects of fluidized-bed combustion for steam generation	190,000 (FY '69) 267,000 (FY '70)
III-g	Characterization and control of air pollutants from a fluidized-bed combustion unit	NAPCA-DPCE CPA 70-10	Pope, Evans, & Robbins	J. W. Bishop S. Ehrlich E. B. Robison	Evaluate potential of fluidized-bed combustion for controlling air pollution	246,498 (FY '70)
III-h	Conceptual design – fluid-bed combustion systems	NAPCA-DPCE CPA 70-9	Westinghouse Electric Corp. Res. & Devel. Ctr. Pittsburgh, Pa.	Dr. B. W. Lancaster Dr. D. L. Keairns	Develop conceptual designs of three fluidized-bed boilers (60, 300 and 600 mw)	344,487 (FY '70)
III-i	Solvent refined coal cost study	NAPCA-DPCE CPA 22-69-82	General Tech. Corp.	Dr. R. G. Shaver	–	38,272 (FY '69)
III-j	Conduct studies on sulfur control by means of coal gasification	NAPCA PH 86-68-65	Scientific Res. Instruments Corp.		Study kinetics of coal gasification techniques on a laboratory scale	241,884 (Total)
III-k	Technological and economic feasibility study of advanced power cycles and methods of producing nonpolluting fuels	NAPCA-DPCE CPA 22-69-114	United Aircraft Res. Lab. East Hartford, Conn.	A. A. LeShane	Define and evaluate advanced techniques for thermal-cycle electrical power generation to reduce pollutant emissions	292,654 (FY '69)

Table III-6. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
III-l	High-sulfur combustor study	NAPCA-DPCE CPA 22-69-151	Chemical Const. Co. New York, N.Y.	J. Belding G. McClellan I. Shah	Select, design, and evaluate a high-sulfur combustor and sulfur-recovery processes	231,728 (Total)
III-m	NO_x from coal combustion	NAPCA-DPCE Interagency transfer	Bureau of Mines	D. Bienstock R. L. Amsler E. R. Bauer, Jr	Evaluate the factors involved in NO_x formation during coal combustion	–
III-n	Development of two-stage coal combustion process	NAPCA-DPCE CPA 70 – 146	Black, Sivalls, & Bryson	–	Determine the feasibility of a new coal combustion-process wherein primary combustion occurs in a molten iron bath and secondary combustion occurs in a normal boiler	225,000 (FY '70) 667,561 (FY '71)
III-o	Study of resistivity and conditioning of fly ash	NAPCA CPA 70 – 149	Southern Res. Inst.	–	Assess electrostatic precipitator performance improvement and capital and operating costs of flue gas conditioning systems	78,665 (FY '70)
III-p	Effect of two-stage combustion and low-O_2 firing in reducing nitrogen oxide emissions from fossil-fuel-fired steam generators	City of Los Angeles Dept. Water & Power	City of Los Angeles Dept. Water & Power Los Angeles, Calif.	–	Evaluate effort of two-stage combustion and low excess air firing on reducing NO_x emissions	–
III-q	Study combustion phenomena of utility boilers to minimize formation of oxides of nitrogen	Southern Calif. Edison Co.	Southern Calif. Edison Co. Los Angeles, Calif.	–	Determine parameters which influence NO_x emission from gas- and oil-fired utility boilers	–

R&D OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Sixteen R&D opportunities related to control of pollution from central-station power plants by combustion modification are recommended in the following areas:

- Laboratory and field investigations of means to suppress NO_x by:
  - low-excess-air combustion
  - flue-gas recirculation
  - two-stage combustion
  - fuel selection
- Development of new power-plant combustion concepts permitting control of SO_x, NO_x, or ash emissions, such as:
  - high-turbulence combustion
  - fluidized bed
  - gasification
  - electrochemical oxidation.
- Analytical and experimental investigations to promote means of retaining ash and slag within the furnace, or of altering the ash so as to promote its collection by downstream equipment.
- Development of research instrumentation for measuring conditions existing in central-station power-plant furnaces and carrying out a program of obtaining such measurements.

Descriptions and evaluations of these R&D opportunities are presented in the following pages. The priority ranking of these opportunities is summarized in the table at the end of this chapter.

R&D Opportunity: III-1 Related to: III-p

Experimental Investigation of Feasibility of Burning Pulverized Coal With Low Excess Air

Technical Objective and Approach

The objective is to determine changes from conventional practice necessary to burn coal in suspension with essentially stoichiometric quantities of air with the intent of improving downstream control of ash, reducing the formation of SO_3 from SO_2, and possibly gaining some control of NO_x formation. Accomplishing this objective may require improved burners, finer-sized coal, and higher turbulence levels in the furnace.

The approach should include laboratory-scale combustion studies to provide the basic information and development studies on larger prototype systems.

Rationale and Incentive

Fuel technologists have been successful in burning residual fuel oil with no more than 1.0 percent excess air in the flue gas, with many advantages demonstrated for such low excess air. If pulverized coal could also be burned with low excess air rather than with 15 percent excess air, as is common today in large boiler furnaces, the problem with emissions would be eased. Advantages are that the volume of flue gas would be reduced appreciably and more effective control of particulates would be possible, higher efficiency would be achieved (meaning less thermal pollution of the atmosphere), no SO_3 would be present in the stack, and low excess air would limit NO_x formation.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $450-$1,000 Recommended 5-year Funding, 1000's: $500

R&D Time Range: 3-5 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	125	125	250	–	–	–

Evaluation

Sources Affected: Coal Power Stations

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						10-25			5-20	–
Expected						16			11	–
Fraction of ECC Emissions Affected						0.15			0.50	–
Noncombustion Controls Factor						0			0.7	–
Relative Potential Benefit Factor						2.40			1.65	4.05

Implementation Time, years: 5-10 most likely: 7 Relative Implementation Cost: Medium

Relative Priority Rating: D

An explanation of the evaluation factors used in the priority ranking is contained in Chapter II and Appendix A.

R&D Opportunity: III-2

Related to: III-3, 4; VIII-27; III-a, b, c, q

Analytical and Experimental Research to Develop Criteria for the Application of Flue-Gas Recirculation to Minimize NO_x Emission from Central-Station Power Plants

Technical Objective and Approach

The objective is to develop criteria for the application of flue-gas recirculation to large boiler furnaces.

The approach should include studies of the quantity of flue gas required, the point of injection, and methods of mixing the flue gas with either the combustion air or burning gases. The influence of flue-gas temperature and composition (as determined by the fuel and fuel-air ratio) on the effectiveness of recirculation and method of recirculation should also be studied. Experimental work with laboratory and pilot-scale equipment should be supported by analytical studies. Flue-gas recirculation in an existing central-station plant should be demonstrated.

Rationale and Incentive

Recirculation of flue gas to decrease the formation of NO_x has been demonstrated on a small scale and in a limited way on a large scale, but little factual information is available on the volume of flue gas to be recirculated, its composition, its temperature, and the point at which it is injected into the furnace. Probably related principally to lowering flame temperature, recirculation should be investigated extensively on both a laboratory and a plant scale to learn whether this process is adaptable to large boiler furnaces. Identifying optimum values for each of these parameters is necessary to assure maximum effectiveness of this method of controlling NO_x emission.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $6,000-$10,000
R&D Time Range: 4-6 years

Recommended 5-year Funding 1000's: $7,600*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	850	1050	2500	3000	10,000*

Evaluation

Sources Affected: Coal, Oil, and Gas Power Stations
Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						75-90				–
Expected						81				–
Fraction of ECC Emissions Affected						0.22				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						17.82				17.82

Implementation Time, years: 4-6 most likely: 5

Relative Implementation Cost: Medium

Relative Priority Rating: B

R&D Opportunity: III-3

Related to: III-2, 4, 5; VIII-27, III-a, b, c, m, p, q

Experimental Investigation to Develop Design Criteria for the Application of Two-Stage Combustion for NO_x Control, With Demonstration in a Coal-Fired Central-Station Power Plant

Technical Objective and Approach

The objective is to develop design criteria for application of two-stage combustion for NO_x control to pulverized-coal-fired boiler furnaces.

The approach should be: (1) to determine the feasibility of such application, (2) to develop design criteria if warranted, and (3) to demonstrate the process on a large scale. The program should involve work with laboratory and pilot-scale furnaces. The investigation should aim at determining the extent to which temperatures in the final stage could be reduced, and the effect of the amount of heat extracted between stages on the rate of burning of the coal particles and the behavior of the ash. Optimized conditions should be sought for each stage and the reduction in NO_x emission should be determined. Finally, a full-scale two-stage combustion furnace should be designed, built, and demonstrated in an operating power plant.

Rationale and Incentive

Two-stage combustion has been demonstrated at power plant scale as a successful method of reducing the emission of NO_x from gas-fired boilers. However, as yet, no studies of this process as applied to the much more common coal-fired plants appear to have been made. The earliest downfired furnaces for firing pulverized coal employed essentially a two-stage combustion process, and this suggests that two-stage combustion with pulverized coal may be feasible.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $11,000-$15,000

R&D Time Range: 5-8 years

Recommended 5-year Funding, 1000's: $2,200*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	200	400	400	1000	10,000*

Evaluation

Sources Affected: Coal Power Stations

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						20-80				–
Expected						50				–
Fraction of ECC Emissions Affected						0.125				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						6.25				6.25

Implementation Time, years: 8-12 most likely: 10

Relative Implementation Cost: Low

Relative Priority Rating: B

R&D Opportunity: III-4

Related to: III-2, 3, 5; VIII-27; III-a, b, c, p, q

Experimental Investigation to Develop Design Criteria for Application of Two-Stage Combustion for NO$_x$ Control, With Demonstration in an Oil-Fired Central-Station Power Plant

Technical Objective and Approach

The objective is to develop design criteria for optimizing the application of two-stage combustion to gas- and oil-fired power plants.

The approach should involve determination of optimum geometries, heat release for each stage, and amount of heat extraction between stages. Both laboratory and pilot-scale equipment should be used. The results should be demonstrated in a full-scale oil-fired power plant boiler because such a plant presents difficulties not presented by gas-fired plants.

Rationale and Incentive

Two-stage combustion, applied in a relatively crude way, has been demonstrated to reduce NO$_x$ emissions from a gas-fired power plant. Optimization of the process has promise of making substantially greater reductions of NO$_x$. Additionally, the application of two-stage combustion to oil-fired power plants should be investigated. It is expected that, while the problem with oil firing will be more difficult, essentially the same optimization criteria will apply to both gas- and oil-fired boilers.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $1,500-$3,000
R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $1,800*

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	200	300	300	1000	–	–

Evaluation

Sources Affected: Oil and Gas Power Stations
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO$_x$	Lead	SO$_x$	Ash	Σ
% Reduction, Range						50-80				–
Expected						72				–
Fraction of ECC Emissions Affected						0.047				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						3.38				3.38

Implementation Time, years: 3-8 most likely: 5

Relative Implementation Cost: Very Low

Relative Priority Rating: B

R&D Opportunity: III-5

Related to: III-3, 4; VIII-25; III-c

Exploratory Research and Experimental Feasibility Evaluation of a Low-Emission Combustion System for Central-Station Power Plants Using the Concept of a High-Turbulence Primary Combustion Zone Plus a Plug-Flow Zone

Technical Objective and Approach

The objective is to investigate the feasibility of applying modern combustion knowledge to the design of large boiler furnaces, with the intent of ultimately reducing the production of pollutants.

The approach should include analytical and design studies of the feasibility of designing a boiler furnace consisting of a well-stirred region followed by a plug-flow region. If feasibility is indicated, laboratory and pilot-scale studies of the burning of residual oils and pulverized coal in such furnaces should be conducted. The results will provide assurance of feasibility and establish the major design parameter needed for ultimate full-scale applications.

Rationale and Incentive

Current understanding of the combustion process indicates that the "optimum" combustion process (from the viewpoint of efficient use of furnace volume) consists of a well-stirred region followed by a plug-flow region. This type of combustion process might lead to emission reduction as all air and fuel elements theoretically would have the same time-temperature history and no inhomogeneities would exist.

Current boiler furnaces are not believed to approach this ideal sequence. Research to demonstrate the feasibility of such a process and to investigate how the variables influence the emission of pollutants is needed. A major part of the development of such a process is not directly associated with pollutant control, however.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $1,600-$2,500

R&D Time Range: 5-8 years

Recommended 5-year Funding, 1000's: $950

	'69-70	71	72	73	74	75	'76+
Funding by Fiscal Year, $1000's	–	100	150	150	250	300	1000

Evaluation

Sources Affected: Coal, Oil, and Gas Power Stations

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-90	0-90				0-50			0-90	–
Expected	22	22				12			22	–
Fraction of ECC Emissions Affected	0.10	0.0017				0.16			0.36	–
Noncombustion Controls Factor	0.65	0				0			0.7	–
Relative Potential Benefit Factor	0.77	0.04				1.92			2.38	5.11

Implementation Time, years: 5-15 most likely: 10

Relative Implementation Cost: High

Relative Priority Rating: D

R&D Opportunity: III-6

Related to: III-7; VIII-20; III-e

Experimental Investigation of the Combustion Mechanism of Coal in a Fluidized Bed of Noncombustible Particles

Technical Objective and Approach

The objective is to develop needed data on the complicated situation existing when particles of coal are burned in close contact with inert particles to which they are transferring thermal energy. A further complication that should be studied is the interaction between burning and inert particles as it affects the diffusion inward of oxygen and outward of CO and CO_2 around each particle of coal.

The approach should consist of experimental investigation of the many variables involved under controlled conditions. Burning tests of single particles of various coals in simulated fluidized beds should be undertaken to provide a better understanding of this phenomenon.

Rationale and Incentive

Much information has been developed over the past 50 years on the burning of single particles of coal suspended in a stream of air. Similarly, devolatilization of a coal particle and combustion of the residual coke need to be investigated under the special conditions of closely surrounding inert particles to determine their influence on the combustion process. Such a study should result in a sufficiently detailed understanding of the mechanism of combustion in fluidized beds to permit establishing optimum conditions in large fluidized-bed combustors.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$600
R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	125	125	250	–	–	–

Evaluation

Sources Affected: Coal Power Stations
Relative Potential Benefit (overall rating): High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						25-75		50-99	0-50	–
Expected						40		71	15	–
Fraction of ECC Emissions Affected						0.12		0.46	0.34	–
Noncombustion Controls Factor						0		0.3	0.7	–
Relative Potential Benefit Factor						4.80		22.86	1.53	29.19

Implementation Time, years: 8-15 **most likely:** 10

Relative Implementation Cost: Medium

Relative Priority Rating: A

R&D Opportunity: III-7 **Related to: III-6; VIII-20; III-e**

Experimental Investigation of Factors Influencing Completeness of Coal Combustion in Fluidized Beds With Low Excess Air

Technical Objective and Approach

The objective is to determine the amount of excess air needed in fluidized-bed combustors to keep CO and unburned fuel at a reasonably low level. The aim should be to provide more adequate information on the optimum conditions in the fuel bed for the best possible utilization of the fluidizing air, the effect of reactivity of the fuel, and the influence of heat-extracting surfaces.

The approach should include an experimental program, conducted on a small laboratory scale, to define the factors influencing the minimum amount of air needed to burn different coals in fluidized beds. This research should permit identification of conditions under which CO can be kept to levels not exceeding 0.1 percent and carryover of unburned fuel can be lowered to the equivalent of carryover in existing combustion systems.

Rationale and Incentive

The type of fluidized-bed combustor receiving most attention today operates with a fixed air supply, to provide fluidization, and controlled small amounts of coal in the combustor. Idealized conditions to ensure full utilization of the coal are not yet definable, and reports of unburned fuel carryover and CO in the flue gas with nominal amounts of excess air vary greatly between different experimenters.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$600
R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	50	75	125	250	–	–

Evaluation

Sources Affected: Coal Power Stations
Relative Potential Benefit (overall rating): High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						25-75		50-99	0-50	–
Expected						40		71	15	–
Fraction of ECC Emissions Affected						0.12		0.46	0.34	–
Noncombustion Controls Factor						0		0.3	0.7	–
Relative Potential Benefit Factor						4.80		22.86	1.53	29.19

Implementation Time, years: 8-15 most likely: 10

Relative Implementation Cost: Medium

Relative Priority Rating: A

R&D Opportunity: III-8

Related to: III-j, k

Development of Improved Coal-Gasification Systems to Produce Sulfur- and Ash-Free Gas Suitable for Advanced Power Cycles

Technical Objective and Approach

The objective is to devise a gasifier to deliver hot clean gas to a combustion system with particular attention paid to removal of H_2S from the hot fuel gas before it is burned.

The approach should include an investigation of such possibilities as cyclone, fluid-bed, and pulverized-coal-suspension gasification. Development of a preferred system should be carried through pilot scale to a stage where a full-scale demonstration is feasible.

Rationale and Incentive

Advanced power cycles (e.g., burning fuel gas in a pressurized furnace with heat extraction followed by expansion through a gas turbine) could well provide entirely new ways of generating electricity at efficiencies as high as 60 percent with minimum emission of air pollutants. To implement such schemes, a coal-gasification process that will yield a hot gas efficiency at reasonable cost is needed. Sulfur removal from the hot gas is a necessary feature if the process is to be practical from an air pollution viewpoint. With a successful method of removing sulfur from the hot fuel gas, SO_2 emission could be essentially eliminated and NO_x could be more easily controlled. The higher efficiency attainable would also ease the overall emission problem.

It should be noted that while the sulfur-removal process and development of the power cycle are not included within this combustion-oriented development, they are necessary accompaniments and their influence on the gasification process is considerable.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: \$850-\$2,000

Recommended 5-year Funding, 1000's: \$1,000

R&D Time Range: 4-6 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, \$1000's	X	100	125	150	300	325	–

Evaluation

Sources Affected: Coal Power Stations

Relative Potential Benefit (overall rating): Very High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	45-90					30-90		50-100	50-100	–
Expected	69					60		75	75	–
Fraction of ECC Emissions Affected	0.095					0.13		0.48	0.36	–
Noncombustion Controls Factor	0.7					0		0.3	0.7	–
Relative Potential Benefit Factor	1.97					7.80		25.20	8.10	43.07

Implementation Time, years: 5-15 **most likely:** 10

Relative Implementation Cost: High

Relative Priority Rating: A

R&D Opportunity: III-9

Exploration of the Feasibility of Electrochemical Oxidation of Coal for Direct Energy Conversion

Technical Objective and Approach

The ultimate objective is to determine the feasibility of coal fuel cells as sources of central-station (or the equivalent) power.

Because of the difficulty of the problem and the expected remoteness of a successful coal fuel cell, no detailed approach can be given. However, a limited program to keep abreast of fuel cell work by others and to investigate problems peculiar to coal fuel cells is most appropriate until the state of the art has advanced to the point where a useful definite approach can be identified.

Rationale and Incentive

Fuel cells using coal as the fuel may offer a long-range solution to the need for supplying large quantities of electrical energy without excessive emissions. Electrochemical oxidation of coal will probably be carried out at relatively low temperatures thus avoiding formation of large quantities of NO_X. The generation of other pollutants is uncertain and would depend on details of the as-yet-unknown process.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $250-open

R&D Time Range: 5 years-open

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	100	100	100	100	100/year

Evaluation

Sources Affected: Coal Power Stations

Relative Potential Benefit (overall rating): Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-100	0-100	0-100	0-100		0-100			0-100	–
Expected	17	17	17	17		17			17	–
Fraction of ECC Emissions Affected	0.017	.0004	.0007	0		0.030			0.059	–
Noncombustion Controls Factor	0.7	0	0	0		0			0.7	–
Relative Potential Benefit Factor	0.09	0.01	0.01	0		0.51			0.30	0.92

Implementation Time, years: 15-20 **most likely:** 18

Relative Implementation Cost: High

Relative Priority Rating: E

R&D Opportunity: III-10

Related to: VIII-2; III-b, m

Laboratory-Scale and Field Investigation of the Effect of Rank of Coal on Emission of NO_x

Technical Objective and Approach

The objective is to determine the influence of coal rank on the formation of NO_x.

The approach should involve experimentally burning coals of various ranks in a laboratory or pilot-scale furnace simulating a central-station boiler furnace. The effect of combined nitrogen in the various coals should be determined. Finally, trials should be conducted in power-plant boilers with coals of several ranks.

Rationale and Incentive

Bituminous coal is burned most commonly today for generating electricity, but most of our reserves are of lower rank coals. Generally these are also low in sulfur. There is a gradual trend toward using these coals, but little is known about their tendency to form NO_x during combustion. Because of the fuel's high moisture content, flame temperatures may be low and NO_x formation minimal. In general, the rank of coal needs to be assessed as affecting NO_x formation, not only for the sub-bituminous coals but for other coal ranks as well.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$300
R&D Time Range: 1-3 years

Recommended 5-year Funding, 1000's: $150

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	75	75	–	–	–	–

Evaluation

Sources Affected: 15 Percent of Coal Power Stations
Relative Potential Benefit (overall rating): Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						0-50				–
Expected						42				–
Fraction of ECC Emissions Affected						0.028				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						1.18				1.18

Implementation Time, years: 2-5 most likely: 3

Relative Implementation Cost: Very Low

Relative Priority Rating: D

R&D Opportunity: III-11 **Related to:** VIII-2

Laboratory-Scale Investigation of the Effect of Residual Fuel-Oil Properties and Composition on Emissions, and Development of Convenient Methods to Characterize Oils in Terms of Emission Tendency, Including NO_x and Particulates

Technical Objective and Approach

The objective of this research program is to investigate the relative pollutant-forming tendencies of different residual fuel oils and to develop convenient analytical methods for classifying such oils as to their pollutant-forming tendencies.

The approach should involve burning residual oil samples in a laboratory furnace to classify them as to their tendency to form particulates and NO_x and possibly other pollutants such as PNA. Should significant differences be found with different oils, a search should be made for convenient analytical methods for classifying the oils. Combinations of physical properties and easily measured chemical properties should be investigated as potential measures of the pollutant-forming tendencies of the oils.

Rationale and Incentive

A number of simple physical tests and other indices have been developed for distillate fuels to characterize their combustion performance (i.e., smoke tendency). Such combustion indices are limited in the residual oil area, and their application as measures of pollutant-forming tendencies has not been explored even in the case of distillate fuels. Simple procedures, either empirically derived indices or analytical tests of properties, to classify residual oils on the basis of their pollutant-forming tendency would be useful in the specification of these fuels for critical areas. Indices could also be useful in establishing fuel-oil standards.

One specific question that needs to be answered is the contribution of nitrogen compounds in the fuel oil to NO_x emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $350-$550 **Recommended 5-year Funding, 1000's:** $475

R&D Time Range: 3-4 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	125	150	200	–	–	–

Evaluation

Sources Affected: 10 Percent of Oil Power Stations and Industrial Steam

Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						0-50				–
Expected						42				–
Fraction of ECC Emissions Affected						0.003				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.13				0.13

Implementation Time, years: 2-5 **most likely:** 4 **Relative Implementation Cost:** Very Low

Relative Priority Rating: E

R&D Opportunity: III-12

Related to: III-13; III-o

Experimental Investigation of the Effect of Mineral Composition of Coal on Fly-Ash Resistivity and Other Characteristics

Technical Objective and Approach

The objective is to identify the characteristics of the coal most important in predicting precipitator efficiency and to provide a useful means of selecting coals when high fly-ash collection efficiency is important.

The approach should be to identify the minerals in coal by a petrographic examination, burn the coal under closely controlled laboratory conditions, and determine the electrical resistivity of the ash. By examining a large number of coals of markedly different mineral composition, it should be possible to decide which minerals or combinations of minerals have the greatest influence on electrical properties of the fly ash.

Rationale and Incentive

Factors related to the composition of the coal being burned in large central-station power plants have never been correlated with the ability of electrostatic precipitators to capture fly ash from that coal.

A factor undoubtedly influencing the electrical resistivity of fly ash is the forms of the minerals providing the inorganic matter in coals. Of the hundred or so minerals eventually forming fly ash, probably less than a dozen have any significant influence on the surface properties of fly ash establishing electrical resistivity.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $150-$350
R&D Time Range: 1-3 years

Recommended 5-year Funding, 1000's: $275

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	75	75	125	–	–	–

Evaluation

Sources Affected: Coal Power Stations
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range Expected									0-50	–
Fraction of ECC Emissions Affected									18	–
Noncombustion Controls Factor									0.59	–
Relative Potential Benefit Factor									0.7	–
									3.19	3.19

Implementation Time, years: 3-6 **most likely:** 5 **Relative Implementation Cost:** Low

Relative Priority Rating: C

R&D Opportunity: III-13

Related to: III-12; III-o

Analytical and Experimental Investigation of the Effect of Combustion Conditions on Fly-Ash Resistivity and Other Characteristics

Technical Objective and Approach

The objective is to identify means of improving the efficiency of electrostatic precipitators by controlling resistivity of fly ash by modifying the combustion process.

The approach should be to determine how combustion conditions affect the electrical properties of fly ash by burning selected coals in the laboratory under conditions approaching those in a large boiler furnace. Rate of burning, particle size, amount of excess air, and rank of coal should be varied so that the factors that affect the resistivity of fly ash can be determined.

Rationale and Incentive

The ability of an electrostatic precipitator to capture particles of fly ash depends largely on the electrical resistivity of the fly ash. When the electrical resistivity exceeds 2 x 10^{10} ohm-centimeters, the normal voltage gradients in a precipitator are upset and the collection efficiency drops abruptly.

Formation of sulfates condensed on the outer surface of fly-ash particles is generally considered to control the resistivity of fly ash. Conditions under which these electrically conductive films form are not known. In fact, it is not certain that sulfates are even responsible, although there seems to be a relationship between sulfur content of the fuel and the resistivity of the fly ash. The state of oxidation, the degree of sintering, and the high-temperature-induced reactions between fly-ash particles also may be involved.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$600

R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $450

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	50	100	150	150	–	–

Evaluation

Sources Affected: Coal Power Stations

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range									0-90	–
Expected									28	–
Fraction of ECC Emissions Affected									0.68	–
Noncombustion Controls Factor									0.7	–
Relative Potential Benefit Factor									5.71	5.71

Implementation Time, years: 2-5 **most likely:** 3 **Relative Implementation Cost:** Low

Relative Priority Rating: C

R&D Opportunity: III-14

Related to: III-15

Analytical and Experimental Investigation of the Feasibility of Fluxing Coal Ash for Minimizing Emission of Particulates From Central-Station Power Plants

Technical Objective and Approach

The objective is to determine the feasibility of adding fluxes to coal-fired boiler furnaces to encourage capture of ash as slag. A secondary objective is to determine whether the use of fluxes will permit burning of low sulfur coals in existing slag-tap and cyclone furnaces.

Feasibility and economics of fluxing in cyclone furnaces, and in ordinary slag-tap furnaces, should be evaluated initially by analytical studies based on available information and then by tests in full-scale boiler furnaces.

Rationale and Incentive

Slag-tap and cyclone furnaces convert much more of the ash in coal into molten slag than do the more common dry-bottom pulverized-coal-fired boiler furnaces. This lower dust loading in the flue gas eases the requirements for downstream mechanical and electrostatic collectors.

Decreasing the viscosity of coal-ash slags will tend to increase the amount of ash converted to slag, thereby decreasing the dust loading in the flue gas. Fusibility of coal ash varies widely, but addition of inexpensive fluxes such as limestone (CaO) and mill scale or iron ore (Fe_2O_3) can lower slag viscosity appreciably.

Also, low sulfur coals normally have high ash fusion temperatures and cannot be burned in existing slag-tap and cyclone furnaces. The use of fluxes may permit such furnaces to burn low sulfur coals, thus decreasing the emission of sulfur oxides.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$600
R&D Time Range: 2-5 years

Recommended 5-year Funding, 1000's: $300

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	100	100	–	–	–

Evaluation

Sources Affected: 100 Percent Coal Power Stations for Ash; 20 Percent Coal Power Stations for SO_x
Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range								50-90	25-90	–
Expected								73	52	–
Fraction of ECC Emissions Affected								0.13	0.59	–
Noncombustion Controls Factor								0.3	0.7	–
Relative Potential Benefit Factor								6.64	9.20	15.84

Implementation Time, years: 4-5 **most likely:** 5 **Relative Implementation Cost:** Medium

Relative Priority Rating: B

R&D Opportunity: III-15 **Related to: III-14**

Analytical and Experimental Investigation of a Super-Slagging Furnace to Achieve High Capture of Coal Ash for Central-Station Power Plants

Technical Objective and Approach

The objective is to demonstrate the feasibility of capturing perhaps 99 percent of coal ash as molten slag in large boiler furnaces.

One approach is through improved cyclone burners. The investigation should cover increased swirl, geometry changes, and optimized operating temperatures. Additionally, this study should determine whether it would be possible by specific design to increase substantially the ash capture of a conventional slag-tap furnace. Studies of ash-particle agglomeration and deposition should be carried out. Subscale and analytical work will be needed.

Rationale and Incentive

Coal-fired cyclone furnaces capture about 90 percent of the coal ash as slag, but the dust loading is still high. If 99 percent conversion of ash to slag could be achieved, the dust loading would be nearly equivalent to that with residual fuel oil, making practical the use of bag filters for ultimate clean-up of the flue gas. Such a super-slagging furnace could be a more economical way of decreasing dust loading than using electrostatic precipitators ahead of a bag filter. Except where complete removal of fly ash is necessary, the super-slagging furnace alone would lead to a nearly clean stack.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $800-$1,500 **Recommended 5-year Funding, 1000's:** $1,100
R&D Time Range: 4-8 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	100	150	150	300	400	–

Evaluation

Sources Affected: Coal Power Stations
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range									45-90	–
Expected									55	–
Fraction of ECC Emissions Affected									0.36	–
Noncombustion Controls Factor									0.7	–
Relative Potential Benefit Factor									5.94	5.94

Implementation Time, years: 8-12 **most likely:** 10 **Relative Implementation Cost:** Low

Relative Priority Rating: C

R&D Opportunity: III-16 **Related to: III-2, 3, 4**

Development of Improved Research Instrumentation and Sampling for Measurement of Local Conditions Within Combustion Systems

Technical Objective and Approach

The objective is to develop new instrumentation for determining more exactly the conditions existing in local regions within boiler furnaces.

The approach should be to develop methods for measuring instantaneous temperatures, gas velocity, and direction of gas flow in large central-station boilers, plus flame volume and position, localized heat transfer, and dust loading. A special case is measurement of spot temperature fluctuation in fluidized beds.

Utilizing this equipment, measurements should be made in several sizes and designs of boiler furnaces to provide data on conditions existing in these units. These data, which are lacking at the present time, may suggest ideas for modifying the combustion process in boiler furnaces to reduce emissions.

Rationale and Incentive

A major problem in relating fundamental studies of combustion to the improvement of large combustors such as boiler furnaces, as well as the empirical improvement of such furnaces, has been the inability to define conditions in these systems adequately. Dust-laden, high-temperature gases moving in nearly random fashion in extraordinarily large enclosures pose as-yet-unsolved problems in measurement. If conditions within the furnace cavity can be measured, a huge step will have been made in defining better how the combustion process can be modified or controlled to minimize furnace emissions.

As an example, better agglomeration of ash particles to form large particles of fly ash would permit their capture by mechanical systems and ease the load on electrostatic precipitators. This agglomeration can be achieved most readily if temperature patterns, residence time, and collision rate during and immediately following combustion are known and controlled.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $350-$1,000
R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	150	150	100	–	–

Evaluation

Although funding the R&D Opportunity described above will not contribute directly to reducing emissions, it will provide data useful to other R&D. A judgmental evaluation was used to assign the Relative Priority Rating to this R&D Opportunity.

Relative Priority Rating: C

R&D Opportunity: III-New Concepts

Provision for Exploring New Concepts and New R&D Opportunities that Evolve from the Program, Accelerating Promising R&D, or Conducting Demonstrations of Promising Concepts for Reducing Emissions from Central-Station Power Plants by Combustion Modification

Technical Objective and Approach

The objective is to provide for long-range flexibility in the R&D program to enable APCO to take advantage of opportunities that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the R&D program to explore the feasibility of new and novel concepts and to accelerate research, development, and demonstration of promising concepts for reducing emissions by combustion-process modification. Worthwhile ideas for combustion-process modification to reduce emissions from central-station power plants might originate as the result of novel design concepts or through in-depth understanding derived from well-planned R&D. The merits of specific R&D opportunities should be decided by evaluating the particular concepts as they evolve.

Rationale and Incentive

No radical changes in large power plants have occurred over the past 30 years, but the necessity of constructing as much generating capability in the next 8 years as exists today and the pollution problem suggest that new ways of converting fuels into electricity will be sought by many scientists and engineers.

One example of a novel concept is the proposed application of the fluidized bed to central-station power plants. Other concepts for combustion modification might result from the development of a radically new heat engine or from combining presently known cycles in a unique fashion.

Recommended Funding Allocation

	'71	'72	'73	'74	'75	
Funding by Fiscal Year, $1000's	–	250	350	400	500	5-year Funding, 1000's: $1,500

Evaluation

This R&D Opportunity is unranked. Potential benefit, implementation time, implementation cost, and funding level for each specific opportunity must be evaluated when the opportunity is identified. The suggested funding level anticipates effort on several R&D opportunities.

Relative Priority Rating: N

TABLE III-9. SUMMARY BY PRIORITIES

CENTRAL-STATION POWER PLANTS

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
A	III-6	Experimental Investigation of the **Combustion Mechanism of Coal in a Fluidized Bed** of Noncombustible Particles	X	125	125	250	–	–	500	–
A	III-7	Experimental Investigation of Factors Influencing **Completeness of Coal Combustion in Fluidized Beds with Low Excess Air**	X	50	75	125	250	–	500	–
A	III-8	Development of Improved **Coal Gasification Systems** to Produce Sulfur- and Ash-Free Gas Suitable for **Advanced Power Cycles**	X	100	125	150	300	325	1,000	–
		Totals, Priority A		275	325	525	550	325	2,000	
B	III-2	Analytical and Experimental Research to Develop Criteria for the Application of **Flue-Gas Recirculation** to **Minimize** $\mathbf{NO_x}$ Emission from Central-Station Power Plants	X	200	850	1,050	2,500	3,000	7,600*	10,000*
B	III-3	Experimental Investigation to Develop Design Criteria for the Application of **Two-Stage Combustion** for NO_x Control, with Demonstration in a Coal-Fired Central-Station Power Plant	X	200	200	400	400	1,000	2,200*	10,000*
B	III-4	Experimental Investigation to Develop Design Criteria for the Application of **Two-Stage Combustion** for NO_x Control, with Demonstration in an Oil-Fired Central-Station Power Plant	X	200	300	300	1,000	–	1,800*	–
B	III-14	Analytical and Experimental Investigation of the **Feasibility of Fluxing Coal Ash** for Minimizing Emission of Particulates from Central-Station Power Plants	–	100	100	100	–	–	300	–
		Totals, Priority B		700	1,450	1,850	3,900	4,000	11,900	

TABLE III-7. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
C	III-12 Experimental Investigation of the Effect of **Mineral Composition of Coal on Fly-Ash Resistivity** and Other Characteristics	X	75	75	125	–	–	275	–
C	III-13 Analytical and Experimental Investigation of the **Effect of Combustion Conditions on Fly-Ash Resistivity** and Other Characteristics	X	50	100	150	150	–	450	–
C	III-15 Analytical and Experimental Investigation of a **Super-Slagging Furnace** to Achieve High **Capture of Coal Ash** for Central-Station Power Plants	–	100	150	150	300	400	1,100	–
C	III-16 Development of Improved **Research Instrumentation** and Sampling for Measurement of Local Conditions **Within Combustion Systems**	–	100	150	150	100	–	500	–
	Totals, Priority C		325	475	575	550	400	2,325	
D	III-1 Experimental Investigation of Feasibility of **Burning Pulverized Coal with Low Excess Air**	–	125	125	250	–	–	500	–
D	III-5 Exploratory Research and Experimental Feasibility Evaluation of a Low-Emission **Combustion System** for Central-Station Power Plants using the Concept of a **High-Turbulence Primary Combustion Zone Plus a Plug-Flow Zone**	–	100	150	150	250	300	950	1,000
D	III-10 Laboratory-Scale and Field Investigation of the **Effect of Rank of Coal on Emission of NO_x**	–	75	75	–	–	–	150	–
	Totals, Priority D		300	350	400	250	300	1,600	

TABLE III-7. (Continued)

Relative Priority Rating		R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
E	III-9	Exploration of the Feasibility of **Electrochemical Oxidation of Coal** for Direct-Energy Conversion	–	100	100	100	100	100	500	100/yr
E	III-11	Laboratory-Scale Investigation of the **Effect of Residual Fuel-Oil Properties and Composition** on Emissions, and Development of Convenient **Methods to Characterize Oils** in Terms of Emission Tendency, Including NO_x and Particulates	–	125	150	200	–	–	475	–
		Totals, Priority E		225	250	300	100	100	975	
N	III-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations** of Promising Concepts for Reducing Emissions from Central-Station Power Plants by Combustion Modification	–	–	250	350	400	500	1,500	–
		Totals, All Priorities		1,825	3,100	4,000	5,750	5,625	20,300	

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Chapter IV

INDUSTRIAL PROCESSING

Herbert R. Hazard

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CHAPTER IV

INDUSTRIAL PROCESSING

SCOPE OF CHAPTER AND BACKGROUND

This chapter discusses combustion for thermal processing in industry, which includes all uses of heat for processing, but does not include steam generation, power generation, or space heating. The principal sources of pollutant emissions in thermal processing are:

- Iron production
- Steel production
- Cement and lime production
- Glass melting
- Aluminum production
- Brick, tile, and ceramic production

Several important fuel uses were excluded because they were considered to be conversion processes rather than combustion applications. These include the blast furnace, the foundry cupola, the coke oven, and ore-roasting plants. The effluents from these plants are not combustion products in the usual sense, because they contain extremely high quantities of process effluents such as CO, SO_2, and particulates.

EMISSION LEVELS FROM THERMAL PROCESSING IN INDUSTRY

Table IV-1 summarizes the contribution of the thermal processing industries to total U.S. pollutant emission levels as a percentage of the total. These percentages are based on the tonnages listed in Table IV-2, obtained by apportioning about 30 percent of industrial combustion fuels to the thermal processing area.

Emissions in Table IV-1 that are large enough to warrant attention are combustible particulate, PNA, NO_x, and SO_x. Emissions of CO and gaseous HC are relatively low.

Most pollutants from industrial processing sources are not subject to reduction by modification of the combustion process. For example, the particulates include those from thermal processing in which the finest fractions of the processed materials or ash escape with the combustion gases; such particulate emission would normally be reduced by means of dust collectors rather than by combustion modifications. Likewise, the SO_x emissions reflect use of thermal processing to remove sulfur from ores and metals, and SO_x cannot be reduced by combustion modifications. PNA is probably largely unburned volatile matter from coal combustion; most of it may originate from steel-industry coke ovens, and it can be reduced only by improved containment during the coking process.

Table IV-1. Emissions From Thermal Processing in Industry*

Pollutant	Contribution to Nationwide ECC Emissions, percent
Products of Incomplete Combustion	
Combustible particulate	6
CO	1
Gaseous HC	1
PNA	4
NO_x	3
SO_x	5
Ash (noncombustible particulate)	3

*Derived from data in Table II-1.

However, NO_x, formed in the combustion process under conditions of high flame temperature and available oxygen, can be significantly reduced by modification of combustion conditions to reduce either temperature or oxygen availability. Accordingly, the combustion R&D opportunities discussed in this chapter are concerned entirely with reduction of NO_x from industrial combustion processes.

Sources of NO_x from Thermal Processing

Table IV-2 lists large thermal processing industries, the fuel thermal input to each, and estimates of NO_x concentrations and emission levels for each. The values of thermal input were taken from a series of American Gas Association reports, *A Study of Process Energy Requirements for U.S. Industries*(2). Values are based on data from the *1962 Census of Manufactures*(1) with much of it updated to 1966.

The values of NO_x concentration in the exhaust gas include Battelle estimates, data from the Esso NO_x study(3), and values based on recommended emission factors for industrial applications from Reference 3. These values are based on ppm NO_2 by volume in exhaust gas corrected to stoichiometric conditions.

The values of tons NO_x per 10^{12} Btu are based upon the fact that the volume of exhaust gas per Btu is nearly independent of fuel type, so that the weight of NO_x per unit of

Table IV-2. Estimate of NO_x Emissions From Various Thermal Processes in Industry

	Fuel Usage, 10^{12} Btu/yr	NO_x Concentration, ppm NO_x in Flue Gas	NO_x Emission	
			Tons NO_x per 10^{12} Btu	Tons NO_x per Year
Iron Production				
Blast furnace	(840)	–	–	–
Blast furnace air preheating	200	10	7	1,400
Iron ore pelletizing	27	500	348	9,400
Iron sintering	80	500	348	27,000
Steel Production				
Open-hearth furnaces	425	270	200	85,000
Steel soaking pits	198	200	140	27,800
Reheat furnaces	300	200	140	42,000
Heat treating	79	200	140	11,000
Iron and Steel Foundries				
Air preheat for gray-iron cupolas	8	50	35	300
Malleable-iron melting and heat treating	12	200	140	1,700
Steel melting and heat treating	14	200	140	1,900
Aluminum Production				
Alumina calcining	96	300	224	21,500
Scrap smelting	12	200	140	1,700
Foundry melting	6	200	140	800
Heat treating	9	200	140	1,300
Copper Production, All Uses	52	200	140	7,300
Zinc Production	41	200	140	5,800
Cement and Lime Production	518	360	250	129,000
Rotary cement kilns	423	360	250	(105,000)
Lime kilns	95	360	250	(24,000)
Glass Melting and Processing	132	625	435	87,000
Ceramic Kilns	145	300	224	32,600
Baking – Bread, Biscuits, Etc.	54	40	27	1,500
Total	3,686			496,000

heat value depends almost entirely upon the NO_x concentration, in ppm. The tabulated values are based upon exhaust-gas weight of 927 lb per 10^6 Btu, and NO_x calculated as NO_2, so that each ppm of NO_x accounts for 0.7 ton NO_2 per 10^{12} Btu.

The total NO_x emission level from the sources listed in Table IV-2 is 496,000 tons per year, which is approximately 5 percent of total U.S. emission of NO_x. This is less than the value of 11 percent in Table I-2, obtained by apportioning total emission from industrial sources among the three major categories: industrial boilers, gas engines, and thermal processing. The source of the discrepancy is not evident, but the difference may be attributable to either error in the apportioning process or lack of accuracy of emission factors used in making various NO_x emission inventories.

Table IV-3 summarizes emission levels from important industrial sources of NO_x, as estimated in the Esso systems study of NO_x(3). The method of calculating these values was entirely different from the method used for calculating values in Table IV-2, being based upon emission per ton of product, and total product output in the base period (1968). However, the values in the two tables are in relatively good agreement and satisfactory for purposes of identifying significant NO_x sources.

Table IV-3. Esso Estimates of NO_x Emission Levels for Thermal Processing(3) (1968)

Source	NO_x Emission, tons per year	NO_x Concentration, ppm
Cement and lime kilns	129,000	200–400
Glass melting	110,000	137–1320
Open-hearth furnaces	85,000	500–800
Iron sintering	27,000	–
Ceramic kilns	21,000	3–70
Blast-furnace stoves	20,000	1.7–6.6
Coke ovens	6,000	45
Cupolas	805	13
Soaking pits	550	21–25
Total	399,000	–

Of the sources in Tables IV-2 and IV-3, those large enough to warrant R&D toward reduction of NO_x emissions appear to be cement, lime, and alumina kilns; glass melting and processing furnaces; open-hearth furnaces; and, possibly, soaking pits, reheat furnaces, and heat-treating furnaces used in the steel industry. The results of research on glass-melting furnaces and open-hearth furnaces could be applied to other reverbratory furnaces used for melting aluminum, copper, brass, and malleable iron, although these are relatively small emitters of NO_x.

In the case of blast-furnace stoves, R&D for control of NO_x by combustion modification does not appear warranted. The Battelle and Esso estimates are 1,400 and 20,000 tons per year, respectively; both estimates are relatively small, and the difference is the result of different estimating approaches. It is important to note that the Esso data indicate that the concentration of NO_x in the exhaust from these stoves is only 1.7 to 6.6 ppm, which is so low that it appears impractical to reduce it further by combustion modifications. The NO_x concentration is low because of the low heating value of blast-furnace gas (90 Btu per ft^3); flame characteristics are similar to those obtained with very large ratios of flue-gas recirculation.

The open-hearth furnace is a somewhat special case because it is being replaced rapidly by the basic oxygen furnace. Although a large percentage of the present open-hearth capacity will have been replaced by 1990, the projected 1990 emission of 30,000 tons NO_x per year from this source will still be significant, and some research toward its reduction appears justified.

Table IV-4 summarizes the projected growth rates and NO_x emissions for significant NO_x sources, based on Reference 4 for growth rates, Reference 5 for open-hearth furnace production rates, and Reference 3 for NO_x emission factors. It can be seen that NO_x emission from cement and lime kilns and from glass-melting furnaces should double by 1990; emission from iron-ore pelletizing machines should increase by a factor of 1.8; and emission from open-hearth furnaces should decline significantly. Total emissions should increase by 57 percent by 1990 if no control measures are implemented.

Table IV-4. Projected NO_x Emissions From Selected Industrial Sources

	Growth Rate(a), %	Projected Emissions, tons/year				
		'68	'70	'75	'80	'90
Rotary Kilns						
Cement and Lime Kilns	3.2	129	138	161	188	258
Alumina Calcining Kilns	2.3	21	22	25	28	35
Glass-Melting Furnaces	3.2	110	118	138	160	220
Clay Tile, Brick, and Ceramic Kiln	3.2	21	23	26	31	42
Open-Hearth Furnaces(b)	–	85	72	54	44	30
Iron-Sintering Machines	–	27	27	27	27	27
Iron-Ore Pelletizing Machines	2.3	9	10	11	13	16
Steel Forming and Heat Treating	2.3	81	85	95	106	134
Totals		483	–	–	–	762

(a) From Reference 4.

(b) Projected production rates from Reference 5, emission factors from Reference 3.

Prospects for Reduction of Emission Levels

As has been discussed, NO_x emissions are the only significant emissions that can be effectively reduced through modification of the combustion processes involved in thermal processing. All of the thermal processing industries are mature industries in which combustion equipment has undergone continuing development over many years. This development has made possible optimum process quality control and economics, but it has not been greatly concerned with pollutant emissions except for visible smoke and particulate emissions, which have been regulated. Moreover, there is incentive for industry to operate large furnaces as efficiently as is practical, so that emissions of products of incomplete burning are minimized.

NO_x is formed by oxidation of the nitrogen in the fuel and in the combustion air, under conditions of high temperature in the presence of oxygen. Thus, formation of NO_x can be minimized by:

- Minimizing flame temperature
- Burning under reducing conditions
- Two-stage burning which achieves low flame temperatures and reducing conditions.

Flame temperature can be minimized by recirculating flue gas through the flame as a diluent to limit peak temperature, by using a large amount of excess combustion air as a diluent, or by two-stage burning with heat removal from the flame before addition of air to complete the combustion.

Burning under reducing conditions, with less than stoichiometric air, limits the availability of oxygen and, thus, reduces formation of NO_x. However, this results in combustion products containing a high proportion of unburned fuel components which must be burned later in the process by addition of air.

Two-stage combustion is a combined process in which fuel is burned under reducing conditions, following which heat is removed from the combustion products and the remaining fuel is burned under oxidizing conditions, but at a temperature low enough to limit the oxidation of nitrogen. A variant of two-stage combustion is carried out without heat removal between stages in the gas turbine, where the short residence time for the second stage of combustion kinetically limits NO_x emission.

The possibility of applying flue-gas recirculation, burning under reducing conditions, or two-stage burning to the thermal processing industries varies with each type of equipment. Accordingly, these are considered separately in the following discussion of possible R&D approaches.

R&D APPROACHES TOWARD REDUCTION OF NO_x THROUGH COMBUSTION MODIFICATION

There appears to be a good probability that the NO_x emissions projected in Table IV-4 can be reduced significantly through modification of the combustion process and that, with moderate success, the total emission levels through 1990 can be held at or near present levels. Combustion modifications that appear most suitable for all processes are: (1) recirculation of exhaust gas into the burners to reduce peak flame temperatures and (2) modification of burners to delay mixing and produce effects similar to those in two-stage burning. The means for carrying out these modifications, the problems that will be encountered, and the probable level of success will vary from process to process. Some of the processes for which R&D benefits are foreseen are discussed below.

Rotary Kilns

Rotary kilns are used for production of Portland cement, the calcining of lime, and the calcining of alumina. In all of these, the kiln is a slightly inclined rotating tube fired at the lower end and fed with raw material at the higher end. Kiln lengths vary from 150 to 500 feet and diameters from 12 to 25 feet. Many kilns are fitted with dust collectors and with air heaters to regenerate exhaust heat.

Cement Kilns. In 1967, there were 188 cement plants in operation in the U.S. Portland cement is made in large kilns fed with a mixture of clay and limestone (or similar materials) plus minor ingredients to provide a carefully proportioned mixture of calcium, silicon, aluminum, and iron. The ground ingredients are slowly heated to 2200 F, at which temperature they react exothermally and quickly reach 2700 F. A long flame, with slow mixing of air and fuel, is used to control the temperature distribution in the kiln and the position of the hot reaction zone. Recuperative air heaters are usually used to recover exhaust heat and to preheat combustion air to about 500 F.

In view of the critical nature of the heat distribution within the kiln, it is not obvious whether modifications of the fuel and air admission at the burner end of the kiln could accomplish the effect of two-stage combustion; in fact, the conventional system may approach this condition. However, it does appear possible to apply exhaust-gas recirculation to cement kilns by ducting exhaust gas to the burner with preheated inlet air and, thus, reducing peak flame temperature. It is not clear how much recirculation could be maintained without reducing kiln temperature or capacity, or what level of NO_x reduction could be achieved. However, it appears possible that NO_x could be reduced by as much as 50 percent.

Lime Kilns. In 1967, 33 of 209 plants accounted for 63 percent of U.S. lime produced(2). Eighty-five percent of the commercial U.S. lime is produced in rotary kilns(2). Lime kilns, for calcining of limestone, normally operate much like a cement kiln, except that the limestone is heated to only 2200 F. During dead-burning of dolomitic limestone to make refractories, however, the lime is heated to 2500 F or more. Because of the moderate temperature level and the absence of a specific reaction zone, modification of lime kilns to reduce NO_x by either burner changes or exhaust-gas recirculation appears to offer a high probability for success.

Alumina Kilns. In 1967, all U.S. production of alumina was concentrated in eight plants. Alumina-calcining kilns, like lime kilns, operate at a moderate temperature of 2200 F, so that the possibility of successful application of flue-gas recirculation or burner modifications to reduce NO_x emissions appears good. The annual thermal input to alumina calcining kilns is about equal to the input to lime kilns, and the reaction temperatures are the same, so that it is probable that the same type of combustion modifications would be applicable to both. It appears possible to reduce NO_x emissions by 50 percent or more by combustion modifications.

Glass-Melting Furnaces

Most glass is melted in large continuous-melting tanks that are regenerative furnaces operating at high temperatures. Incoming air is heated to a high temperature in brick checkers, and exit gas is cooled in a second set of checkers. The flow direction is reversed periodically to maintain both sets of checkers at similar temperatures and thus maintain constant firing conditions. Flame temperature is near 3500 F, and the process temperature is maintained at the highest level possible consistent with satisfactory refractory life. The combination of high air preheat and hot refractory temperature results in high flame temperature and high NO_x concentrations, reported to be in the range from 435 to 1320 ppm(3). However, the actual glass temperature during the refining period is only about 2700 F, so that it appears possible to reduce peak flame temperature significantly and, thus, reduce NO_x emission, without greatly reducing production rate.

The chemistry of the glass being melted determines whether an oxidizing or reducing flame is required, so that two-stage burning does not appear generally compatible with production requirements. However, it appears desirable to alter burner mixing patterns to provide slow mixing and long flames and, thus, avoid high local temperatures. In addition, it may prove feasible to utilize an effective level of flue-gas recirculation to further reduce maximum local flame temperature without greatly reducing mean furnace radiating temperature. In view of the long residence time and high temperature level in the glass-melting furnace, it is unlikely that NO_x can be reduced to a low level, but a reduction of as much as 50 percent of current emission levels appears attainable if optimum conditions can be determined and maintained.

Open-Hearth Furnaces

Open-hearth furnaces, like glass tanks, are large reversible regenerative reverbratory furnaces in which chemical reactions and heating take place. In processing a batch of iron to make steel, scrap is melted, molten iron is added, and the metal is slowly heated and refined under a layer of slag. The making of steel is an oxidation process, with oxygen provided from iron ore added to the bath, by use of oxygen lances through the roof, by reduction of carbon dioxide evolved from limestone, and by oxidation from the combustion atmosphere above the bath. Combustion takes place under oxidizing conditions at high temperature, limited only by the temperature limits of the furnace refractories. The NO_x levels vary between 500 and 800 ppm. The use of oxygen injection through lances directed into the bath, and under the burners to increase flame temperatures near the bath, but not near the roof, provides local regions of high flame temperature conducive to high NO_x emissions.

It is probable that measures to control or reduce NO_x may also reduce furnace productivity, but some significant NO_x reduction may be possible with acceptable productivity levels. As with glass tanks, the most attractive solutions appear to be flue-gas recirculation to minimize high peak temperatures without greatly reducing mean radiating temperature, and modification or adjustment of burners to provide more gradual mixing and combustion.

The number of open-hearth furnaces in service is scheduled to decline from 467 units in 1968 to 257 units in 1973, with a further gradual decline through 1990 because the newer basic oxygen furnace operates at significantly lower cost when the cost of particulate emission controls is included. However, the projected emission of NO_x from open-hearth furnaces in 1990 is 30,000 tons per year, which is still significant.

Iron-Ore Pelletizing Machines

In 1968, nine iron-ore pelletizing machines in the U.S. produced 45,000,000 tons of pelletized ore, with estimated NO_x emission of 9,400 tons. These machines are located at, or close to, the iron mines producing the ore, and burn heavy oil or natural gas. It is anticipated that the production of iron pellets will grow at a rate proportional to that of steel production, at about 2.3 percent per year.

In one type of pelletizing machine, pellets formed from a wet slurry of finely divided ore are carried upon a moving belt about 300 feet long while being heated to about 2200 F by combustion products passing through the moving pellet bed. After the pellets have sintered, incoming combustion air is passed upward through the hot pellet bed to cool the pellets and recover the heat by preheating the combustion air. Heavy oil or natural gas is burned in a refractory chamber above the pellet bed, many burners being used to control temperature distribution. Flame radiation to the bed is avoided to minimize excessive heating of the surface of the pellet bed.

The highest gas temperature utilized in the pellet bed is about 2500 F, and all fuel is burned in conventional burners. Thus, it appears possible to reduce present NO_x emission levels by as much as 50 percent through application of combustion modifications such as flue-gas recirculation or burner modifications.

Iron-Sintering Machines

Iron sintering is carried out within steel mills as a means of recovering and utilizing fine iron oxide dust from plant sources and from dusty ores. The fine oxide is mixed with flue dust, coke breeze, and limestone in a slurry which is fed to the sintering machine. In the sintering machine the sinter is slowly heated to about 2200 F as it passes over a moving belt 60 to 100 feet long. A gas or oil flame in the entrance region brings the sinter to its ignition temperature, after which combustion of carbon within the sinter provides the remaining heat required to sinter the iron. The ignition fuel provides only 1/5 of the total heat.

The Esso estimate(3) for NO_x emission from sintering machines is 27,000 tons per year. In view of the fact that most of the combustion in sintering takes place within the sinter, in which the combustible material is in the form of mixed carbon, the opportunities for reduction of NO_x emission through combustion modifications appear limited. However, it appears possible to minimize the NO_x emission from the ignition flame by burner modifications or flue-gas recirculation. Flue-gas recirculation may also reduce the NO_x emitted from combustion within the sinter.

Because of changes in steel-mill practices, it is anticipated that no new sintering machines will be built, but that those in operation will remain active. Thus, NO_x emission from sintering operations should not grow in the future.

Steel Rolling, Forging, and Heat-Treating Furnaces

Steel rolling, forging, and heat treating accounts for consumption of about 615 x 10^{12} Btu per year of fuel, which is consumed entirely within steel mills. About half of this is coke-oven gas and blast-furnace gas, and the balance is natural gas and fuel oil. The soaking pits, reheat furnaces, and heat-treating furnaces in which this fuel is burned are large and each has many burners, all adjusted to provide the desired temperature distribution and heating conditions within the furnace. Metal temperatures are fairly moderate, less than 2300 F, and combustion conditions are adjusted for highest efficiency without smoke, at near-stoichiometric, but oxidizing, conditions. Actual emission factors for these furnaces are not available, but it seems reasonable to use factors recommended for industrial combustion of natural gas and fuel oil(3), which are equivalent to about 200 ppm NO_x in the exhaust, or 140 tons per 10^{12} Btu.

There appears to be some opportunity to reduce NO_x emissions through combustion modifications. Flue-gas recirculation could reduce peak flame temperatures without greatly reducing mean radiating temperatures, but would require considerable ducting and a revision of combustion controls. Likewise, two-stage burning, with reducing conditions within the furnace and an afterburner at the furnace outlet, would seem possible with some types of furnaces, although means must be found to insert and remove steel from the furnaces without loss of combustible and toxic combustion products. This area appears to require considerable investigation, both to ascertain present NO_x emission levels and to devise acceptable control methods, but R&D appears justifiable as this is a potentially large source with a moderate growth rate.

Fuel-Rich Afterburning for Regenerative Furnaces

Regenerative furnaces are those utilizing exhaust-heated checkers for heating incoming air, such as open-hearth furnaces and glass-melting furnaces. Because of the high temperature levels at which they operate, and the necessity for oxidizing atmospheres for the processes in which they are used, it may prove impractical to reduce NO_x emission to a satisfactory level through combustion modifications within the furnace. An alternative approach would be to use a fuel-rich afterburner to destroy the NO_x in the flue gas, followed by recovery of the heat produced by combustion, and a second afterburner operating at lower temperature to remove unburned fuel remaining from the first afterburner.

Figure IV-1 is a schematic diagram of a fuel-rich afterburner system for one of the two reversible regenerator banks. In this system, fuel such as natural gas is added to the hot combustion products from the furnace to burn out remaining oxygen by partial combustion of the methane to CO and H_2, which takes place readily at elevated temperature. At this temperature, and within the time available, it appears possible that NO can be reduced by the CO and H_2 to an acceptably low level, but kinetic studies are needed to verify this. The hot reducing gas would then pass through the first checker for cooling to about 2000 F. On leaving the first checker, it would pass through a second afterburner where sufficient air would be added to burn the CO and H_2 generated in the first afterburner. The gas, now slightly oxidizing, would pass into the second checker for final cooling. The heat value of the fuel burned in the first afterburner would be recovered in the two checker banks and then added to the incoming air upon reversal of the flow pattern.

It is conceivable that this process could be used for both glass-melting tanks and open-hearth furnaces should it prove practical and economical.

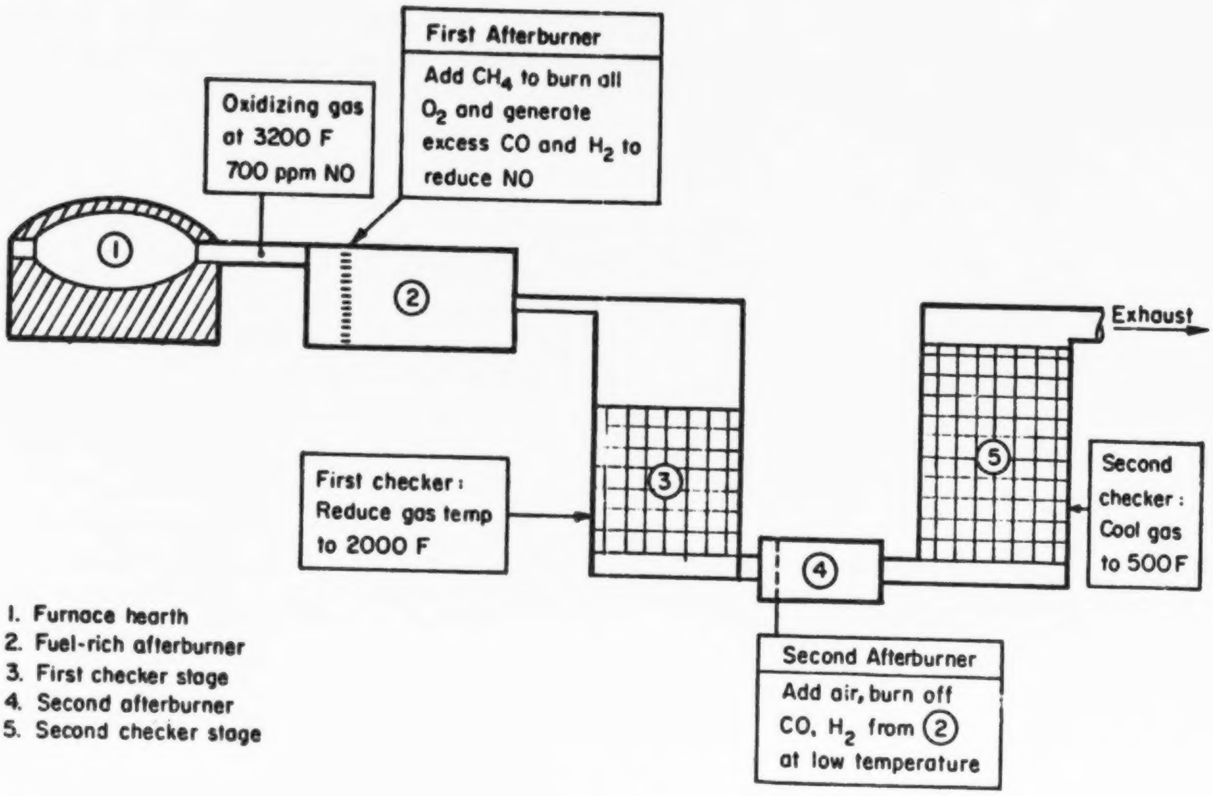
First Afterburner
Add CH_4 to burn all O_2 and generate excess CO and H_2 to reduce NO
Oxidizing gas at 3200 F 700 ppm NO
①
②
Exhaust
③
⑤
First checker: Reduce gas temp to 2000 F
Second checker: Cool gas to 500F
④
1. Furnace hearth
2. Fuel-rich afterburner
3. First checker stage
4. Second afterburner
5. Second checker stage
Second Afterburner
Add air, burn off CO, H_2 from ② at low temperature

Figure IV-1. Schematic Diagram of Fuel-Rich Afterburner System for Regenerative Furnaces

SUMMARY OF CURRENT AND RELEVANT COMBUSTION R&D

Table IV-5 summarizes current combustion R&D programs related to reduction of pollutant emissions from thermal processing industries.

The two Esso programs are industry-wide studies of control methods suitable for reduction of NO_x by all means, but with emphasis on combustion modifications. The second program listed has the objective of identifying and evaluating emissions from combustion sources in the iron, steel, and aluminum industries. The APCO program of demonstration of new sintering-process technology is just beginning.

The research program of the International Flame Research Foundation, at IJmuiden, Holland, merits special comment. This group effort, over a period of many years, has involved studies of detailed effects of flame aerodynamics and mixing, fuel type, and heat-removal rates on the radiation from large flames. Much has been learned about the details of soot formation and decomposition, temperature profiles within flames, and concentration of CO, O_2, and CO_2 throughout flames as combustion proceeds. The facilities and skills which have been developed at this large experimental facility are applicable to detailed study of pollutant generation and decomposition within large flames.

Table IV-5. Current Combustion R&D – Industrial Processing

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
IV-a	Systems study of nitrogen oxides control methods for stationary sources	NAPCA-DPCE PH 22-68-55	Esso Res. & Eng. Co. Linden, New Jersey	W. Bartok	Consider methods for reducing NO_x emissions from stationary sources including industrial processing	389,307 (Total)
IV-b	Selected R&D of nitrogen oxides control methods for stationary sources	NAPCA-DPCE CPA 70-90	Esso Res. & Eng. Co. Linden, New Jersey	–	Obtain improved data on NO_x emissions and determine effect of some control techniques on a limited number of applications	363,025 (FY '70)
IV-c	Evaluation of conventional combustion sources in the iron and steel industry and aluminum industry	NAPCA-DPCE EHSD 71-21	Walden Res. Corp. Cambridge, Mass.	–	Evaluate cost effectiveness of current emissions-control technology, and define needed control for these units	64,268 (FY '71)
IV-d	Demonstration of new technology for controlling all emissions from the sintering process	NAPCA-DPCE CPA 70-Neg. 185	–	–	–	–
IV-e	Various studies related to combustion for industrial processing	Various industrial organizations contribute	International Flame Research Foundation IJmuiden, Holland	W. Leuckel	Studies to determine combustion conditions within flames typical industrial furnaces including heat transfer and velocity, temperature, and concentration profiles.	–

R&D OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Five R&D opportunities in the area of thermal processing in industry were identified. These cover R&D for NO_x reduction in:

- Rotary kilns for cement and lime production
- Glass-melting furnaces
- Open-hearth furnaces
- Regenerative melting furnaces
- Iron-sintering and iron-pelletizing processes.

Descriptions and evaluations of the R&D opportunities are presented on the following pages.

R&D Opportunity: IV-1

Related to: VIII-27, 28; IV-a, b, e

Analytical and Experimental Research on the Reduction by Combustion Modifications of NO_x Emission From Rotary Kilns for Production of Cement and Lime, Including Full-Scale Demonstration Application

Technical Objective and Approach

The objective is to develop information necessary for the modification of firing practice to reduce emission of NO_x from large rotary kilns used in cement and lime production.

The approach should involve examination of possible modifications that might prove applicable such as techniques for minimizing peak combustion temperatures by the use of long-flame burners with delayed mixing of fuel and combustion air and the use of flue-gas recirculation. An analytical model should be used to explore the probable effects of these changes, following which experiments should be carried out in a laboratory-sized, non-rotating kiln model. If significant success is achieved with the laboratory model, the most suitable modifications should be applied to a full-scale lime kiln or a full-scale cement kiln.

Rationale and Incentive

Cement kilns are among the largest stationary emitters of NO_x. Each kiln is large enough to be a significant local emission source. The cement-burning process takes place over a short section of the kiln at 2700 F; extremely high flame and refractory temperatures are not required for satisfactory processing. It is probable that the local high temperatures responsible for high NO_x levels can be reduced significantly without loss of output. Delayed mixing of fuel and air is now used for process control but has not been investigated in relation to NO_x emission; when optimized for NO_x, the mixing patterns may be different. Also, flue-gas recirculation appears applicable to such systems.

This emission source is expected to grow at a rate of 3.2 percent per year, with NO_x emissions increasing from 129,000 tons in 1968 to 258,000 tons in 1990. A reduction of NO_x emissions of about 45 percent appears probable by combustion modifications.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $500-$800
R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $700*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	200	200	200	–	–

Evaluation

Sources Affected: Rotary Kilns for Production of Cement and Lime
Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						0-60				–
Expected						43				–
Fraction of ECC Emissions Affected						.0053				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.23				0.23

Implementation Time, years: 4-6 **most likely:**5

Relative Implementation Cost: Very Low

Relative Priority Rating: E

An explanation of the evaluation factors used in the priority ranking is contained in Chapter II and Appendix A.

R&D Opportunity: IV-2

Related to: VIII-27, 28; IV-a, b, e

Analytical and Experimental Research on the Reduction of NO_x From Glass-Melting Furnaces by Combustion Modifications

Technical Objective and Approach

The objective is to develop information necessary for the modification of firing practice for glass-melting tanks to reduce the emission of NO_x.

This approach should consist of investigating several combustion modifications, for example: (1) use of long-flame burners in combination with considerable internal recirculation, (2) use of flue-gas recirculation, and (3) use of two-stage combustion, where glass chemistry is suitable. The effects of these modifications upon predicted local flame temperatures and NO_x levels should be investigated analytically as a basis for experimental work. Experiments should then be carried out in a day tank (a small batch-type tank). If significant success is achieved at this level, the most suitable modifications should then be made ready for application to a large continuous-melting tank.

Rationale and Incentive

Most glass is melted in large reverberatory furnaces having regenerative brick checkers for heat recovery and air preheating. Flame and furnace temperatures are very high, leading to high emission of NO_x, in the range of 750 ppm. The actual glass melting and refining temperature is about 2700 F; therefore, extremely high overall furnace temperature is not required. Thus it appears possible to modify the combustion practice to minimize peak flame temperature without a significant reduction of roof temperature and mean gas radiating temperature.

This emission source is expected to grow at a rate of 3.2 percent per year, with NO_x emissions increasing from 110,000 tons in 1968 to 220,000 tons in 1990. With a moderate level of success, a reduction of NO_x emissions of about 50 percent appears probable by combustion modifications.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$500

R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $400

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	200	100	–	–	–

Evaluation

Sources Affected: Glass-Melting Furnaces

Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						20-80				–
Expected						50				–
Fraction of ECC Emissions Affected						.0046				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.23				0.23

Implementation Time, years: 4-6 most likely: 5

Relative Implementation Cost: Very Low

Relative Priority Rating: E

R&D Opportunity: IV-3

Related to: VIII-28; IV-a, b, c, e

Analytical and Experimental Research on Reduction of NO_x Emissions From Open-Hearth Furnaces by Modification of Firing Techniques, Including Demonstration

Technical Objective and Approach

The objective is to reduce NO_x emissions from open-hearth furnaces.

The approach should include an analytical examination of the conditions within the open-hearth furnace to determine the effects of local variations in combustion conditions and flame temperatures upon production rates and NO_x emissions. If encouraging results are obtained, a laboratory model should be constructed for experimental investigation of the parameters involved. If laboratory results are promising, experimentation should be followed by application to a full-scale furnace.

Rationale and Incentive

Although a great many open-hearth furnaces have been retired, and more are to be retired in the near future, those remaining will continue to be significant emitters of NO_x. It is estimated that the NO_x emissions from this source will decrease from 88,000 tons in 1968 to 44,000 tons in 1980 and30,000 tons in 1990. A reduction of NO_x emissions of about 50 percent appears possible by combustion modifications.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $500-$2,000
R&D Time Range: 2-5 years

Recommended 5-year Funding, 1000's: $2,000*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	250	250	500	1000	–	–

Evaluation

Sources Affected: Open-Hearth Furnaces
Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						20-60				–
Expected						47				–
Fraction of ECC Emissions Affected						.0009				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.04				0.04

Implementation Time, years: 6-8 most likely: 7

Relative Implementation Cost: Very Low

Relative Priority Rating: E

R&D Opportunity: IV-4

Related to: VIII-28; IV-a, b, c, e

Analytical and Experimental Research on Fuel-Rich Afterburning to Reduce NO_x Emission From Regenerative Melting Furnaces

Technical Objective and Approach

The objective is to reduce NO_x emissions from regenerative furnaces by the use of a fuel-rich afterburner and a second fuel-lean afterburner with heat removal following each afterburner. (See Figure IV-1.)

The approach should be to investigate analytically and then in actual furnaces the effect of adding fuel to the high-temperature gas stream leaving a regenerative furnace, such as an open-hearth or glass-melting furnace, thus providing time for the NO_x to react with the fuel under reducing conditions to decompose the NO_x. The gas should then be cooled by passing it through part of the regenerator, after which air should be added to burn out the CO formed in the fuel-rich afterburner. This would reheat the gas stream somewhat, after which it should be passed through the second regenerator section for final cooling.

Rationale and Incentive

Because of process chemistry limitations, it may not be feasible to reduce NO_x emitted from open-hearth furnaces and from glass tanks by modifications of the combustion process. However, both of these processes operate with regenerators for heat recovery which makes it feasible to add fuel to the exhaust stream and recover the heat of combustion in the regenerator that follows. The fuel-rich afterburning would provide a reducing atmosphere to promote reactions resulting in destruction of NO_x.

The sum of NO_x emissions from glass-melting furnaces and open-hearth furnaces will grow from 195,000 tons in 1968 to 250,000 tons in 1990. A reduction of NO_x emissions of about 50 percent appears possible by combustion modifications.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$1,000

Recommended 5-year Funding, 1000's: $800*

R&D Time Range: 2-4 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	300	300	100	–	–

Evaluation

Sources Affected: Glass-Melting Furnaces and Open-Hearth Furnaces

Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						20-90				–
Expected						52				–
Fraction of ECC Emissions Affected						.0056				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.29				0.29

Implementation Time, years: 4-6 most likely: 5

Relative Implementation Cost: Low

Relative Priority Rating: E

R&D Opportunity: IV-5 Related to: VIII-27, 28; IV-a, b, c, d, e

Analytical and Experimental Investigation of Combustion Modifications to Reduce NO_x Emission From Iron-Sintering and Iron-Pelletizing Processes

Technical Objective and Approach

The objective is the modification of the combustion process to reduce NO_x emissions from iron-pelletizing and sintering machines used in processing iron ore and/or steel-plant iron oxides.

The approach should include analytical investigation of the effect of combustion modifications on the process. The technique that seems best for NO_x reduction should be investigated experimentally in a full-size unit. It is expected that combustion modifications such as two-stage combustion or flue-gas recirculation will greatly reduce NO_x emissions without affecting the processing variables adversely.

Rationale and Incentive

Iron pelletizers are large machines, generally located at the iron mine, used to make hard, often partially reduced, pellets of the finely ground ore. Sintering machines are similar in operation, but are used within steel plants to recover in usable form the finely divided iron oxide collected from plant sources. These machines are fairly large users of fuel, and process requirements are such that high flame temperatures are not essential. Therefore, it appears feasible to apply combustion modifications for reduction of NO_x.

NO_x emissions from these sources are expected to grow at a rate of 6 percent per year, from 27,000 tons in 1968 to 98,000 tons in 1990. A reduction of NO_x emissions of about 50 percent appears possible by combustion modifications.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$500
R&D Time Range: 1-3 years

Recommended 5-year Funding, 1000's: $300

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	200	–	–	–	–

Evaluation

Sources Affected: Iron-Sintering and Pelletizing Plants
Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						30-60				–
Expected						48				–
Fraction of ECC Emissions Affected						.0018				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.09				0.09

Implementation Time, years: 3-5 most likely: 4

Relative Implementation Cost: Very Low

Relative Priority Rating: E

R&D Opportunity: IV-New Concepts

Provision for Exploring New Concepts and New R&D Opportunities that Evolve from the Program, Accelerating Promising R&D, or Conducting Demonstrations of Promising Concepts for Reducing Emissions from Combustion Equipment used for Industrial Processing by Combustion Modification

Technical Objective and Approach

The objective is to provide for long-range flexibility in the R&D program to enable APCO to take advantage of opportunities that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the R&D program to explore the feasibility of new and novel concepts and to accelerate research, development, and demonstration of promising concepts for reducing emissions by combustion-process modification. Worthwhile ideas for combustion-process modification to reduce emissions from combustion equipment used for industrial processing might originate as the result of novel design concepts or through in-depth understanding derived from well-planned R&D. The merits of specific R&D opportunities should be decided by evaluating the particular concepts as they evolve.

Rationale and Incentive

Industry utilizes a variety of thermal processes, each having different problems and combustion restraints. Although these restraints somewhat limit the extent of combustion modification, it appears possible that new concepts for reduction of emissions from specific processes may arise.

Recommended Funding Allocation

	'71	'72	'73	'74	'75	
Funding by Fiscal Year, $1000's	–	50	50	50	50	5-year Funding, 1000's: $200

Evaluation

This R&D Opportunity is unranked. Potential benefit, implementation time, implementation cost, and funding level for each specific opportunity must be evaluated when the opportunity is identified. The suggested funding level anticipates effort on several R&D opportunities.

Relative Priority Rating: N

TABLE IV-6. SUMMARY BY PRIORITIES

INDUSTRIAL PROCESSING
(Combustion for Thermal Processing, not including Steam Generation)

Relative Priority Rating		R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
E	IV-1	Analytical and Experimental Research on the Reduction by Combustion Modifications of NO_x **from Rotary Kilns** for Production of Cement and Lime, Including Full-Scale Demonstration Application	–	100	200	200	200	–	700*	–
E	IV-2	Analytical and Experimental Research on the Reduction of **NO_x from Glass Melting Furnaces** by Combustion Modifications	–	100	200	100	–	–	400	–
E	IV-3	Analytical and Experimental Research on Reduction of **NO_x Emissions from Open-Hearth Furnaces** by Modifications of Firing Techniques, Including Demonstration	–	250	250	500	1,000	–	2,000*	–
E	IV-4	Analytical and Experimental Investigation of Fuel-Rich Afterburning to Reduce **NO_x Emission from Regenerative Melting Furnace**	X	100	300	300	100	–	800*	–
E	IV-5	Analytical and Experimental Investigation of Combustion Modifications to Reduce **NO_x Emission from Iron-Sintering and Iron-Pelletizing Processes**	–	100	200	–	–	–	300	–
		Totals, Priority E		650	1,150	1,100	1,300		4,200	
N	IV-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Combustion Equipment used for Industrial Processing by Combustion Modification	–	–	50	50	50	50	200	–
		Totals, All Priorities		650	1,200	1,150	1,350	50	4,400	

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3. Bartok, W., et al., *Systems Study of Nitrogen Oxide Control Methods for Stationary Sources,* Esso Research and Engineering Company Report GR-2-NOS-69, Prepared under NAPCA Contract No. PH-22-68-55 (November 20, 1969).
4. *An Energy Model for the United States Featuring Energy Balances for the Years 1947 to 1965 and Projections and Forecasts to the Years 1980 and 2000,* Bureau of Mines Information Circular IC-8384 (July, 1968).
5. Varga, J., and Lownie, H. W., *A Systems Analysis Study of the Integrated Iron and Steel Industry,* Battelle Memorial Institute, Final Technical Report, CSTI No. PB 184577, prepared under NAPCA Contract No. PH 22-68-65.

Chapter V

INDUSTRIAL STEAM GENERATION AND COMMERCIAL AND RESIDENTIAL HEATING

R. E. Barrett
D. W. Locklin

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CHAPTER V

INDUSTRIAL STEAM GENERATION AND COMMERCIAL AND RESIDENTIAL HEATING

SCOPE OF CHAPTER AND BACKGROUND

Energy-conversion devices within the source category of Industrial Steam Generation and Commercial and Residential Heating are used primarily for converting chemical energy in fuel to thermal energy in the form of steam, hot water, or warm air. In this chapter, possibilities for pollutant emission reduction by combustion modification are discussed as they pertain to the following applications:

- Industrial
    - steam generation
    - space heating
    - service water heating
- Commercial
    - space heating
    - service water heating
- Residential
    - space heating
    - service water heating

Principal fuels utilized for these applications include:

- Solid fuels
    - bituminous coal
    - small quantities of anthracite coal and lignite
- Liquid fuels
    - residual fuel oil
    - distillate fuel oil
    - liquid-petroleum products (propane and butane)
- Gaseous fuels
    - natural gas

Table V-1 shows the contribution of industrial steam-generation and commercial- and residential-heating sources to nationwide pollutant emissions from energy-conversion combustion processes. (These percentages are based on data in Table II-1). It should be noted that the percentage contributions reported in Table V-1 are for annual emissions. Considerable seasonal variations occur with commercial and residential heating, contributing a significantly higher percentage of emissions for colder localities during the winter.

Table V-1. Emissions From Industrial Steam Generation & Commercial & Residential Heating

Pollutant	Contribution to Nationwide ECC Emissions, percent		
	Industrial Steam Generation	Commercial & Residential Heating	Total
Products of Incomplete Combustion			
Combustible Particulate	36	9	45
CO	nil	1	1
Gaseous HC	<1	1	1
PNA	nil	90	90
NO_x	12	5	17
Combustion-Improving Additives			
Lead, etc.	nil	nil	nil
Fuel Contaminants			
SO_x	19	12	31
Ash (Noncombustible Particulate)	21	4	25

Ranges of fuel-input rates typical of the different applications included within the scope of this chapter are listed in Table V-2. Although these fuel-input rates range up to 600 x 10^6 Btu per hr, emission inventory data for the "industrial" category are generally limited to firing rates below 100 x 10^6 Btu per hr (or about 80,000 lb steam per hr). However, the discussion

Table V-2. Typical Fuel Input Rates(3)

Building Type and/or Use	Range of Fuel Input, 10^6 Btu/hr
Residential:	
Houses and small apartments (1–4 family)	0–1.0
Large, multiple-dwelling, apartments	0.5–5.0
Commercial and institutional:	1–50
Office buildings, hotels, theaters, stores, churches, small colleges, small hospitals, libraries, public buildings, warehousing, and manufacturing (without large process-steam requirements)	
Large commercial and institutional:	10–200
Housing projects, colleges, hospitals, and manufacturing (without large process-steam requirements)	
Small industrial (with large process-steam requirements)	1–100
Large industrial (with large process-steam requirements)	10–600

and R&D opportunities described in this chapter apply to all units smaller than about 500×10^6 Btu per hr. Larger boilers are covered in Chapter III on Central-Station Power Plants; some R&D opportunities described in that Chapter also apply to smaller boilers.

Fuel Consumption for Various Applications*

Figure V-1 shows the quantities of energy used, by fuels, for industrial steam generation for recent years and projections through 1980. These plots were obtained by estimating the percentage of fuel used for steam generation by each industry (based on data in Reference 2) and assuming for each fuel that the ratio of fuel used for steam generation to total fuel consumed by the industrial sector(1) is constant. Oil and gas consumption for industrial steam generation are increasing rapidly, while coal consumption is remaining at a nearly constant rate.

Figure V-2 shows the relative quantities of each fuel used for commercial and residential space heating for recent years and projections through 1980. The use of solid fuels for space heating has been steadily declining, and will continue to decline, with possible exceptions in some localized rural areas. Liquid and gaseous fuels have assumed an increasing share of the space-heating load, and their use will continue to increase in terms of quantity, although the growth of electric heating may cause the percentage of the space-heating market utilizing liquid and gaseous fuels to decline.

Fuel-use data in Figure V-2 represent "retail dealer deliveries to other consumers" (as per Reference 2). This includes primarily household and commercial users; however, some unknown portion of small industrial users likely is included. Although this definition does not match exactly with the energy-use categories in this chapter, it is sufficiently close to represent the general fuel-use pattern for purposes of this study.

Combustion Equipment

Figure V-3 lists the different types of combustion equipment used for industrial steam generation and commercial and residential heating, including typical ranges of the firing rates covered by each type of equipment.

Table V-3 shows the total number of automatic heating units, by major classes, in residential use as of the end of 1969. Figure V-4 shows past and predicted future trends in residential heating units by fuel.

---

*A problem of definition is encountered in surveying the literature on fuel usage and pollutant emissions for narrowly defined source categories. Available data are based on subjective definitions of "commercial and residential", "industrial", and "industrial process". For example, some references use the term "industrial process" without specifying whether it includes or excludes industrial steam raising and industrial space heating. Likewise, the Bureau of Mines energy-model report(1) defines "commercial and residential" fuel as "retail dealer deliveries to other consumers"; practically, this limits fuel consumption to about 1000 gallons fuel oil per month or a firing-rate capacity of about 500,000 Btu/hr. Obviously, this definition of "commercial and residential" fuel usage does not correspond with how the fuel is actually utilized (compare with Table V-2). To make use of available information, the Bureau of Mines definition of commercial and residential fuel usage was accepted. Fuel usage for industrial steam raising was obtained by estimating that portion of each fuel likely to be used for steam generation for each industry. Additional detail regarding these estimates is given in Chapter IV, Industrial Processing.

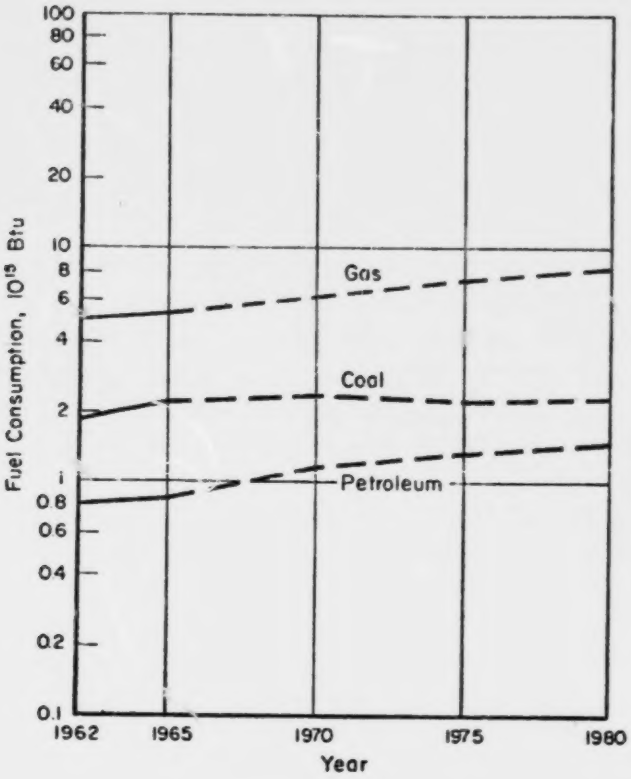


Figure V-1. Fuel Consumption by the Industrial Sector(1)

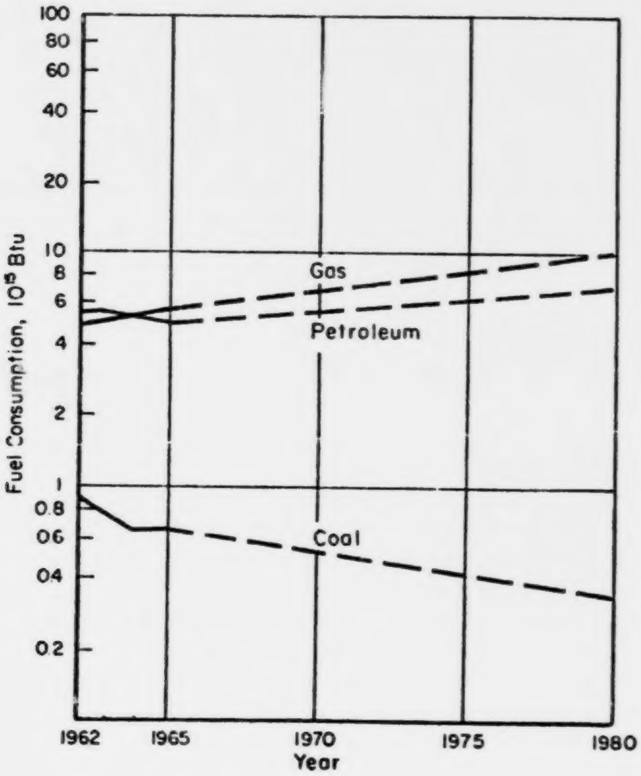
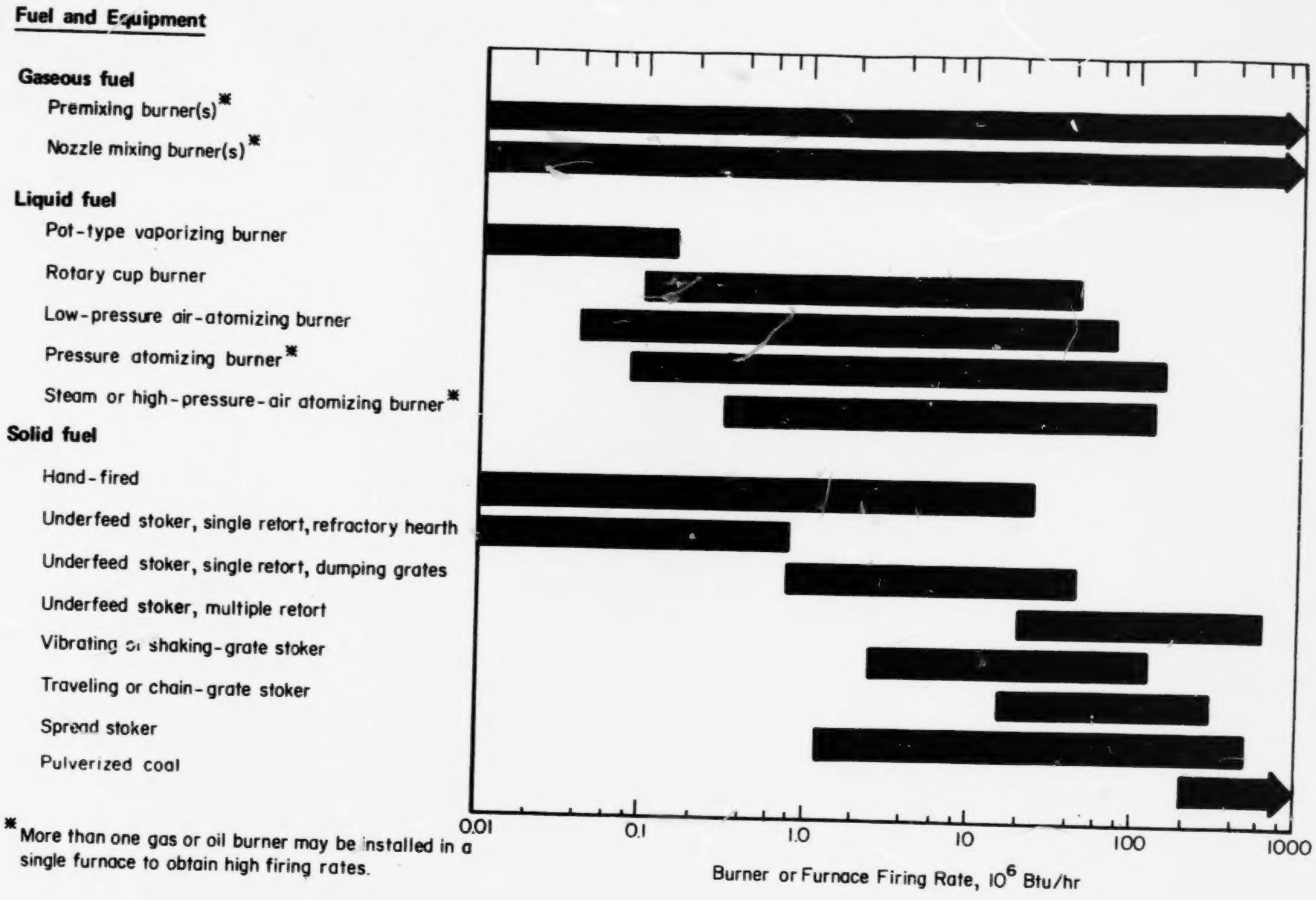


Figure V-2. Fuel Consumption by the Household and Commercial Sector(1)



*More than one gas or oil burner may be installed in a single furnace to obtain high firing rates.

Figure V-3. Types and Firing Rates of Combustion Equipment Used for Industrial Steam Generation and Commercial and Residential Heating (This Information Based on Data in References 3-8).

Table V-3. Automatic Heating Units in Residential Use in 1969[9]

Gas-fired units	19,985,250	**(58.8%)**
Oil-fired units	11,186,650	**(32.9%)**
Oil furnaces	5,800,564	
Oil-fired boilers	5,386,086	
Coal stokers	340,000*	**(<1%)**
Electric-heating units	2,818,745	**(8.3%)**
Total	33,990,645	

*Not included in total.

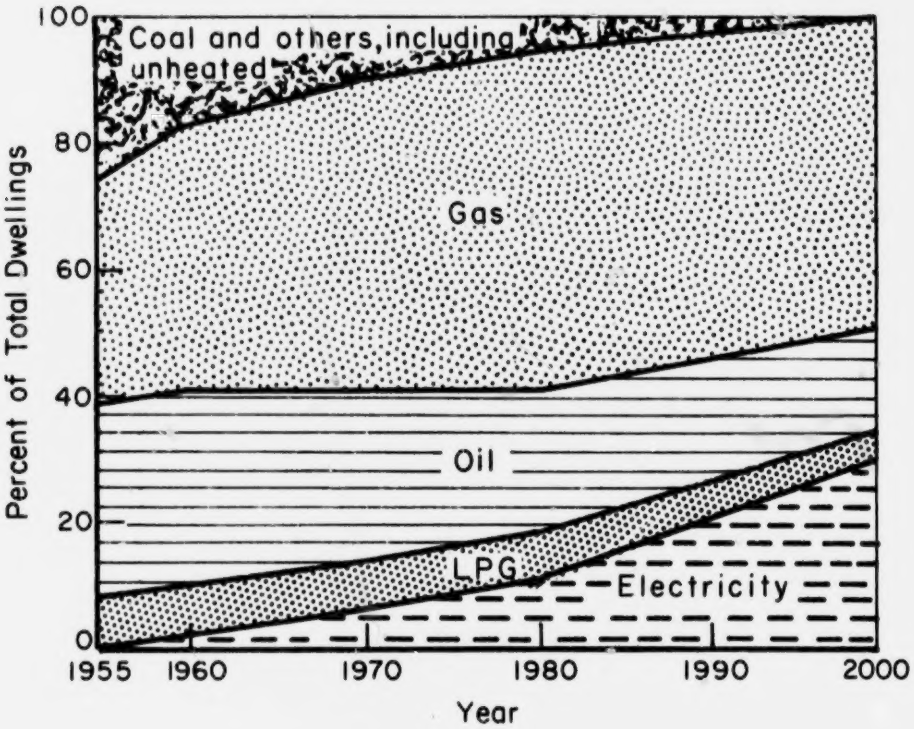


Figure V-4. Fuel-Use Patterns for Residential Home Heating[10]

Pollutants of Principal Concern

Pollutants of principal concern from industrial steam-generation and commercial and residential space-heating combustion processes include:

- Products of incomplete combustion – combustible particulate, CO, gaseous HC, and PNA (odor-producing compounds generally fall in this category)
- NO_X
- SO_X
- Fly ash and other noncombustible particulate.

Emissions of combustible particulate, CO, HC, and PNA are usually associated with incomplete combustion, PNA coming primarily from coal-fired sources. NO_X is formed during combustion either from nitrogen in the fuel or by fixation of atmospheric-nitrogen in the high-temperature flame environment. SO_X and fly ash are generally associated with fuel impurities and are little affected by the combustion process. Noncombustible particulate from coal and residual-fuel-oil combustion include, in addition to fly ash, fuel additives used for various purposes. The ash or additives may contain such trace pollutants as manganese, lead, barium, chlorides, and fluorides.

For applications within the scope of this chapter, pollutants that may be controlled by modification of the combustion process received principal emphasis. These include combustible particulates, CO, HC, PNA, and NO_X.

POLLUTANT EMISSION LEVELS

Although the weight of pollutants emitted by individual units considered in this chapter is low when compared with emissions from combustion units burning large volumes of fuel (power stations), the additive effect of a large number of units operating in densely populated areas can be serious. Also, the low stacks and the low heat content of the exhaust gas from these smaller pollutant sources may cause the pollutants to remain relatively close to ground level where they contribute to the local pollution problem. Therefore, although many of these pollutant sources are small individually, they are worthy of attention because of their concentration in urban areas.

Emission Levels with Present Practice

Table V-4 presents a summary of the pollutant emission factors for major fuels and for several sizes of equipment. Average or "best values"* and ranges are shown where data permit. These data represent uncontrolled pollutant emissions and generally represent average values recommended for use in community air-pollution surveys. Emissions from individual units may vary widely from the average values.

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*"Best values" is defined as the best estimate of average emission levels.

Table V-4. Pollutant Emission Factors From Small- and Intermediate-Size Combustion Sources, Lb/10^6 Btu[(a)]

Pollutant	Natural Gas		Fuel Oil		Coal	
	0-10 x 10^6 Btu/hr[(b)]	10-100 x 10^6 Btu/hr[(c)]	0-10 x 10^6 Btu/hr[(b)]	10-100 x 10^6 Btu/hr[(c)]	0-10 x 10^6 Btu/hr[(b)]	10-100 x 10^6 Btu/hr[(c)]
Products of Incomplete Combustion						
Combustible particulate	0.025	0.024	0.043	0.066	0.45	1.2
CO	0.0004 (0.000-1.3)	0.0004 (0.000-0.13)	0.013 (0.000-0.13)	0.013 (0.000-0.02)	2.3 (0.14-3.5)	0.10 (0.029-0.12)
Gaseous HC	0.004 (nil-0.068)	0.005 (nil-0.0045)	0.013	0.017 (0.013-0.26)	0.55 (0.036-0.77)	0.054 (0.006-0.077)
PNA	0.33	0.22	0.18	0.11	44.0	0.44
NO_x	0.13 (0.07-0.18)	0.20 (0.03-0.35)	0.48 (0.06-0.9)	0.58 (0.47-0.9)	0.18 (0.015-0.31)	0.79 (0.65-0.8)
Fuel Contaminants						
Total particulate	0.025 (nil-0.03)	0.024 (nil-0.03)	0.071 (0.053-0.08)	0.11 (0.053-0.20)	1.0 (0.3-4.5)	2.6 (0.6-17.3)
SO_x	0.008 (0.0004-0.0013)	0.0008 (0.0004-0.0013)	0.27	1.87 (0.3-3.7)	3.15 (0.75-8.3)	3.15 (0.75-8.3)
Noncombustible particulate	nil	nil	0.028	0.044	0.55	1.4

(a) Shown as "best value (range)" based on References 3 and 11-17. Conversion factors used when data in references were given in other units are:

Natural Gas – 1,000 Btu/cu ft
19,000 Btu/lb
Fuel Oil – 150,000 Btu/gal
19,000 Btu/lb
Coal – 13,000 Btu/lb.

(b) APCO defines as domestic and commercial.(15)

(c) APCO defines as industrial.(15)

Table V-5 is a summary of PNA emissions from various types of coal-burning equipment. This table presents a detailed breakdown of the aromatics into specific compounds. Figure V-5 shows the range of benzo(a)pyrene emissions from various sizes of coal-burning units; some data on emissions from oil- and gas-fired units are also included.

Generally, the following observations can be made regarding emissions from sources discussed in this chapter:

Products of Incomplete Combustion

- Combustible particulate, CO, and HC emissions increase with increasing difficulty in air-fuel mixing (natural gas < oil < coal).
- CO and PNA emissions from coal-fired units decrease as unit size increases and better air-fuel mixing and higher temperatures are achieved (hand-fired > nonspreader stoker > spreader stoker). See Figure V-5 for benzo(a)pyrene emissions.
- HC emissions decrease as unit size increases; longer residence times probably permit burning to be more nearly complete.

Nitrogen Oxides

- NO_x emissions increase as unit size increases and are probably related to the higher temperatures achieved in larger units; however, residence time may also be a factor.
- NO_x emissions increase with increasing difficulty in air-fuel mixing (natural gas < oil < coal).

Sulfur Oxides

- SO_x emissions are almost entirely dependent on the sulfur content of the fuel and, except for sulfur pickup by coal ash, are largely independent of firing method.

Fly Ash and Other Noncombustible Particulates

- Noncombustible particulate emissions increase as the ash content of the fuel increases (natural gas < distillate oil < residual oil < coal).

Table V-5. Polynuclear Aromatics Emitted by Bituminous Coal With Various Firing Methods[(a)](3,16)

	Type of Unit								
	Pulverized Firing	Cyclone	Spreader Stokers		Chain-grate Stoker	Underfeed Stokers			Hand-fired
Benzo*(a)*pyrene	0.04-0.31	0.49	0.04	0.057	0.082	22	0.26	8.4	880
Pyrene	0.20-0.40	2.25	0.23	1.30	0.860	35	3.70	17	1,320
Benzo*(e)*pyrene	0.05-0.58	0.87	0.13	0.770	0.290	17	0.510	11.9	220
Perylene	0.15	0.04				3.5			132
Benzo*(ghi)*perylene	0.02-1.42	0.44				9.9		1.28	660
Anthanthrene						0.64			198
Coronene	0.02-0.12	0.01	0.02	0.057		0.73		2.64	66
Anthracene						1.9			880
Phenanthrene						22	2.2	64	2,200
Fluoranthene	0.18-0.85	0.17	0.11	0.790	1.50	83.9	7.1	103	2,200
Benz*(a)*anthracene						8.6		1.23	

(a) From Smith and Gruber(69). Figures are pounds per 10^{12} Btu input.

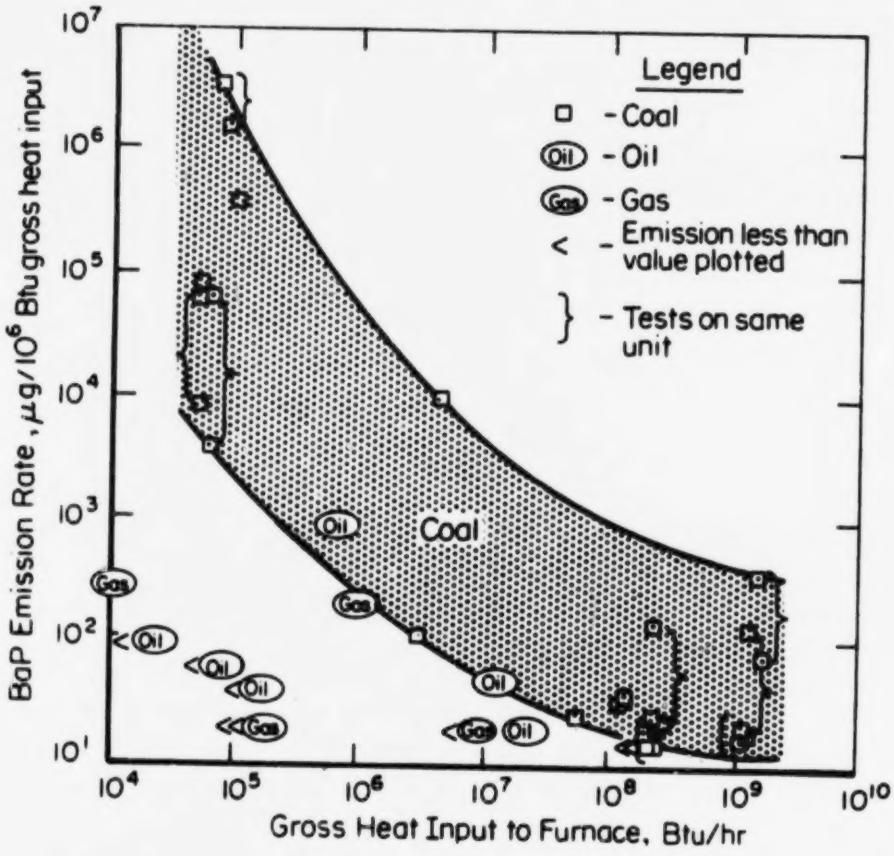

Figure V-5. Benzo(a)pyrene Emissions From Combustion of Coal, Oil, and Natural Gas(18)

To date, there has been only limited control of pollutant emissions from residential and commercial space-heating sources, although smoke control has been enforced locally on larger units to reduce visible particulate emissions, and increasingly strict standards on smoke emissions from oil-fired units have been adopted.(19) The widespread conversion of residential heating from coal to oil and natural gas, which has occurred in the past three decades, has significantly reduced pollutant emissions associated with incomplete combustion and emissions of noncombustible particulate. Additionally, recent regulations for several of the larger cities and federal facilities(20) have limited the sulfur content of coal and fuel oils to reduce SO_x emissions.

With two exceptions, the pollutant-control methods already applied do not represent emission control by modification of the combustion process. Rather, they involve application of simple mechanical devices for removal of particulate from the flue gas of larger coal-fired units, equipment replacement (either with or without fuel substitution), or regulation of the properties of allowable fuels.

The exceptions, where the combustion process itself is affected, are: (1) improved design of oil-fired units to reduce smoke (generally by better atomization and mixing) and (2) application of overfire air to ensure more complete combustion in larger coal-fired units.

Emission Levels Attainable With Latest Technology and Prospects for Future Reduction

With the exceptions already noted (primarily smoke control), there generally has been little incentive to control emissions from industrial steam-generation and commercial and residential heating sources. Thus, historically, little effort has gone into advancing the technology of emission control for these applications, so the emission levels attainable with latest technology probably would not be significantly different from current emission levels as listed in Table V-4. Average data on emissions from general modern oil burners confirms this assumption(21).

Recently there has been increased interest in the development of techniques for controlling emissions from such equipment. Current research in this area will be discussed in a subsequent section of this report.

There appears to be no reason why emission levels cannot be reduced to levels characteristic of the best units by utilizing current technology, upgrading installation and servicing, etc. Reducing emissions to levels below those currently attainable is not an unrealizable goal.

TECHNOLOGY GAPS FOR EMISSION CONTROL BY COMBUSTION-PROCESS MODIFICATION

The first step necessary in determining what combustion R&D is needed to reduce emissions is to identify what is known and what is unknown about how the combustion process affects emissions and how the results of current R&D are likely to contribute. These subjects are covered in the following discussion. A tabulation of current combustion R&D is presented at the end of this section.

GAS, OIL AND PULVERIZED-COAL COMBUSTION

In contrast to coal combustion for industrial steam generation and commercial and residential heating, where a declining market limits potentially attractive R&D opportunities, gas and oil usage for these purposes is increasing at a significant rate and, therefore, longer-term R&D opportunities of a more basic nature can be attractive. Hence, gaps in the basic understanding of the combustion process in gas- and oil-fired small and intermediate-size combustion equipment are discussed, as well as gaps in knowledge pertaining to the application of specific techniques that show promise for reducing emissions. Potential contributions of current R&D in this area are also cited.

Although pulverized-coal combustion is not treated extensively in the following discussion, much of the basic combustion technology would also apply to this fuel.

Basic Understanding of the Combustion Process

Although basic combustion research will probably result in an improved understanding of the relationships between combustion phenomena and burner variables, it will not necessarily have an immediate effect on burner design. Burner design is not a well developed scientific discipline but has been, and still is, partly an art. Most burner designs are arrived at by trial and error and hardware-oriented development, not by direct application of a body of knowledge on the subject of combustion. This is not too surprising, considering the complexity of the combustion process. There are large gaps in the basic knowledge of combustion and its application to burner units, and empirical design equations are limited to simple combustion systems.

However, as more is learned about the combustion process, there is greater hope that more use will be made of general guidelines and relationships between combustion phenomena and burner-design variables. Also, there will be improved understanding of the relationship between pollutant emissions and combustion conditions, so that burners and furnaces can be designed to provide conditions for minimum pollutant generation.

Therefore, although basic combustion research is necessary for future advancement of burner and furnace design from the art stage to a more scientific stage, and for eventual reduction in pollutant formation, the more basic research in this area must be viewed with only cautious optimism with respect to quickly realized reductions in emissions from the classes of combustion equipment covered in this chapter.

Examination of the gaps in the basic understanding of the combustion process might be simplified by considering two different levels of understanding. Ultimately, a comprehensive understanding of the combustion process, as it occurs in small- and intermediate-size combustion equipment, will be needed to construct complete mathematical models describing both the physical and the chemical aspects of the process. Complete models are certainly many years in the future. In the meantime, a better empirical knowledge of relationships between combustion variables, equipment performance, and emissions would be a useful tool for designing equipment.

Mathematical Model of the Combustion Process

A complete physical and chemical description of a generalized combustor design together with the ability to quantify the description to fit the requirements of a specific usage, including minimization of pollutant production, would provide an ultimate tool for the designer. Consideration might be given to how nearly realizable such a tool is, without regard for the economics of its use as compared with other possible design procedures.

In a pure sense, the mathematical model of a combustor would be based on the most fundamental fluid dynamics, chemical, and heat-transfer relations. But in a more practical sense, the designer would be willing to be less basic and use coefficients obtainable from the literature for various parameters, just as he uses pipe size, surface characteristics, and Reynolds number to determine pressure drops in pipes. On this basis, the only questions are whether available computers are capable of handling the number of variables involved, and whether the knowledge of the needed coefficients is adequate.

At the present time, a completely general description of combustion systems is beyond reach, so a specific system consisting of an oil-fired heating unit can be used to illustrate present capabilities. Processes that are involved in the operation that can be described adequately for simple systems on the basis of presently available experimental results are atomization; mixing of the fuel, air, and recirculated flue gas; vaporization; ignition of the fuel; droplet combustion; and flow patterns. Because the combustion rate in practical combustors operating at atmospheric pressure is generally mixing controlled, rather than chemically controlled, it then is possible to describe the gross aspects of the combustion process for simple combustion systems.

The next stage is to computationally allow for the heat transfer from the combustion gases to surfaces, which is the aim of most combustors. This heat transfer is both convective and radiative. The latter becomes increasingly important as the size of the combustor increases, as the carbon-to-hydrogen ratio of the fuel increases, and as the flame temperatures increase. Because radiative transfer from the gas is a volume and not a surface phenomenon, the equations rapidly increase in complexity as finer detail in the combustor structure is included. And, obviously, if the combustion gases lose heat, the factor must be iterated back into the computations. At the present time, considerable effort is being spent in developing routine and practical ways to calculate the convective-radiative heat-transfer portion of the combustion process in practical systems.

For air-pollution problems, one more stage must be involved in the mathematical modeling. The gross flow patterns, composition profiles, and temperature profiles must be used as a basis for defining the various path environments in which pollutants such as NO_x are produced. In general, neither the knowledge of kinetics nor the knowledge of the physical fine structure is adequate to proceed with this stage.

Finally, it should be noted that a combination of mathematical modeling, physical modeling, and prototype experiments can often be used more effectively than any single approach, such as mathematical modeling, to solve the combustion problem at hand.

Empirical Knowledge Relating Combustion Variables to Emissions

Emissions from combustion equipment could be reduced if equipment designers had an empirical knowledge (not necessarily a full understanding) of how important combustion system variables affect pollutant emissions. Historically, such relationships have been defined only for emission of smoke. These relationships were derived from investigations to determine how emission of smoke might be reduced. For instance, it has been known that smoke emission is reduced by increasing turbulence or mixing, flame temperature(22), residence time in the hot zone, and excess air and by improving fuel atomization. Likewise, such approaches can be expected to reduce the other products of incomplete combustion including CO, HC, and odor.

Hence, the three T's of combustion (time, temperature, and turbulence) have been the significant variables at the disposal of designers in their attempts to control the overall combustion process. Temperature may not be freely selected in all cases, as heat-transfer criteria must be considered. Likewise, the efficient use of space may impose limits on time. Power requirements for combustion-air blowers place limits on turbulence. Therefore, combustion-unit designers must make compromises between the requirements for efficient, clean combustion and other considerations such as cost, noise level, and compactness.

In addition, the increasing concern for reducing air pollution is forcing designers to consider pollutant emissions as a major factor in equipment performance. However, despite recent efforts(21,23,24) many of the needed empirical relationships between controllable combustion variables and emission levels have not been developed. To provide designers with the input needed to produce low-emission combustion units, relationships will need to be developed between pollutant emissions and combustion variables such as mixing, turbulence, combustion intensity, flame temperature, residence time, internal recirculation, time-temperature profiles, etc.

Combustion-Equipment Development

Basic combustion-process studies will not be useful unless they result in: (1) the development of new or improved low-emission burners or (2) determination of operating conditions by which present burner emissions can be reduced. However, burner development can proceed without awaiting completion of either of the above-mentioned studies. In fact, a number of efforts have been and are under way to develop low-pollution combustion units.

Because combustion must occur in a limited time (for space efficiency) and at high temperature (for space efficiency and for high heat-transfer rates), conditions favorable to pollutant formation seem difficult to eliminate. Although some reduction in pollutant formation can be expected from burner development efforts, without a background of understanding of the formation of pollutants as part of the basic combustion process, it is difficult to forecast the chances of major successes or breakthroughs that would significantly reduce emissions.

Techniques for Lowering Peak Gas Temperatures

It has been generally accepted that NO_x is formed during the combustion process by the reaction of nitrogen and oxygen atoms.(25,26) Hence, NO_x emissions are associated with high-temperature combustion with excess air. (Some studies sgugest that fuel-bound nitrogen may be the primary source of nitrogen in the formation of NO_x from firing oil and coal; however, further study in this area appears needed.)

Obviously, if NO_x forms in the presence of excess air at high temperatures, two possible approaches to lowering NO_x emissions are to:

- Reduce gas temperatures
- Reduce excessive air, especially in high-temperature regions.

Techniques that have been suggested to accomplish one or both of the above include:

- Flue-gas recirculation
- Two-stage combustion
- Designing combustion devices to achieve low peak temperatures by other means such as catalytic or surface burners, radiant burners, and burners that operate with large quantities of excess air.

While each of these techniques for reducing NO_x appears to have merit, none have been developed to the point where they have proved practical.

Flue-Gas Recirculation. Flue-gas recirculation involves diluting the fuel-air mixture in the combustion zone with cooled flue gases and, thereby, reducing flame temperature rise and peak gas temperature. Utilizing cooled flue gas as the diluent does not adversely affect combustion efficiency as neither the mass nor the temperature of exhaust products need increase.

Several studies(27-31) have shown that recirculated flue gas can also contribute to lower emission of smoke when firing fuel oil. One of these studies(27) reported that CO, HC, and NO_x emissions were held at low levels by recirculation when firing No. 2 fuel oil into a boiler at 1 gph.

Application of flue-gas recirculation to small and intermediate size combustion equipment is limited by knowledge gaps in the following areas:

- Effect on emission levels of variables such as temperature of the recirculated gas, point at which the gas is injected, and quantity of recirculated gas
- Corrosion and deposits associated with recirculation
- Control of recirculated flue gas quantity in equipment operating at variable firing rates
- Start-up problems.

Two-Stage Combustion. Two-stage combustion involves burning fuel in a fuel-rich primary zone, partially cooling the combustion products, and, finally, supplying additional air and completing combustion in a secondary zone. Thus, two-stage combustion makes possible low peak gas temperatures, because the combustion products are cooled before combustion is completed and oxygen levels are low in the highest temperature region – the primary combustion zone. Barnhart and Diehl have demonstrated that conversion to two-stage combustion reduced NO_x emissions from a gas- and oil-fired utility boiler by 30 to 50 percent.(32) Bienstock, Amsler, and Bauer found that, when pulverized coal was burned in a power plant with 5 percent excess air in the primary zone and 17 percent excess air added at the proper location downstream, NO_x emissions did not increase above levels obtained when burning with 5 percent excess air and no downstream air addition.(33) Two-stage combustion has not been demonstrated as practical on smaller combustion units.

Application of two-stage combustion to small- and intermediate-size combustion equipment is limited because of gaps in knowledge of:

- Effect on emissions of important combustion variables such as primary-zone fuel-air ratio, temperature drop between the primary and the secondary zones, and secondary zone fuel-air ratio.
- Possible corrosion associated with reducing conditions in the primary zone.
- How to design combustion equipment to achieve effective two-stage combustion (i.e., how to achieve necessary mixing in the secondary zone, how to achieve burnout of incompletely burned products formed in the primary zone, what the residence-time requirements are for primary and secondary zones, and how to incorporate sufficient cooling between zones without increasing equipment size and emissions of smoke, CO, and HC.)

Other Techniques for Achieving Low-Temperature Combustion. Several other techniques available for achieving combustion at low-peak-gas temperatures include:

- Catalytic- or surface-combustion burners
- Radiant-heating devices
- Combustors that operate at high excess air.

These techniques have not been developed to the point of practical application to heating boilers or furnaces.

Surface combustion has been used successfully on a number of gas-fired infrared or surface heating units. These units operate with combustion zone temperatures of about 1800 F to 2000 F and, although no specific data are available, these units are likely to have low NO_x emission levels. Surface combustion of gaseous fuels could be incorporated into residential heating units with little difficulty, although practical combustion of fuel oil has not been demonstrated for long-term operation. Potential problems with fuel oil include achieving complete combustion, achieving uniform fuel feed across the burner face, and preventing deposits on the burner surface.

Radiant heating devices have potential for operating with low NO_x emissions because the high rate of heat transfer from the combustion zone reduces peak temperature. Incorporating this concept into residential heating units should reduce NO_x emissions from these sources. Development of residential furnaces utilizing radiant burners would require conversion from a convection to a radiant heat exchanger; there is no reason why this is not technically feasible, although equipment might be larger.

Combustion at extremely high air-fuel ratios would obviously reduce peak gas temperatures by dilution. Consequently, NO_x emissions would be reduced below levels for present equipment. However, efficiency would also suffer as the greater mass of flue gas would increase losses. It is difficult to envision how units operating at high air-fuel ratios could be both efficient and have low NO_x emissions. Therefore, this concept appears to have limited value.

Other Investigations

Gaps exist with respect to knowledge of several other phases of the combustion process and combustion-system design, and these gaps may also limit emission control by combustion modification. More information is needed concerning the effect on emissions of transients, of additives and emulsions, and of burner servicing and maintenance.

Transients

Few data relating emissions to transient conditions appear in the literature(21). However, observation of the operation of on-off combustion devices reveals that emission levels of pollutants – like particulates, HC, and odor – are relatively high during transient conditions. Investigations are needed to determine emission levels during transient conditions and the contribution of these emissions to total emissions. If emissions during transient periods are significant on a weight basis, techniques for their reduction should be investigated.

Servicing and Maintenance

Although only scattered data on burner servicing and maintenance are available(34,35), it is known that lack of proper burner adjustment and/or maintenance can result in poor combustion(36) and higher levels of pollutant emissions. This is especially true with regard to pollutants associated with incomplete combustion of the fuel (combustible particulate, CO, and HC). For example, Table V-6 shows smoke measurements before and after burner adjustment on a total of 310 oil-fired units. Burner adjustment, as detailed in Table V-7, produced significantly lower smoke levels, especially from residential burners.

Medium- to large-size combustion units are most likely to receive proper maintenance under service contracts or by onsite operators. Therefore, reasonably good combustion performance of these units should be realized. However, emissions that service personnel and/or operators cannot easily detect (NO_x PNA, etc.) still may not receive proper attention. Education and proper instrumentation will assist in this area.

Conversely, small units such as found in single- to 4-family residences and in small commercial buildings are likely to receive no attention until a forced shutdown occurs. This lack

Table V-6. Smoke Ratings on Tested Oil Burners(35)

Smoke No.	Percent of Burners Before and After Adjustment					
	Domestic Distillate		Commercial Distillate		Commercial Residual	
	Before	After	Before	After	Before	After
0	13	24	17	24	10	14
1	27	50	25	22	15	15
2	16	22	15	32	14	20
3	17	2	13	3	15	21
4	8	0	10	8	15	10
5	8	1	9	7	7	10
6	2	1	3	2	7	3
7	4	0	6	2	4	3
8	3	0	0	0	5	3
9	2	0	2	0	8	1

Table V-7. Oil-Burner Adjustments Related to Reduction in Smoke(35)

	Single Adjustment		Multiple Adjustment	
	Reduction	No Reduction	Reduction	No Reduction
Cleaned nozzle	–	–	24	9
Replaced nozzle	12	5	81	33
Replaced parts or cleaned air intake system	1	5	68	27
Adjusted air intake	23	9	153	93
Adjusted draft	4	5	44	25
Adjusted oil pressure	3	11	51	22
Adjusted oil temp.	–	–	13	15
Changed firing rate	2	7	29	12
Improved* boiler condition	4	5	61	18

*Includes repairing or rebuilding the combustion chamber and cleaning the boiler and scaling air leaks.

of servicing is more likely with natural-gas-fired units than with liquid-fired units as natural gas is received by pipeline and technically trained representatives of the burner or fuel supplier rarely visit the installations. Fortunately, the gaseous fuels are more easily burned and, therefore, gas combustion equipment is simpler so that burner maladjustment is less likely.

Limited efforts that are under way in this area will contribute to the knowledge of relationships between burner maintenance and pollutant formation and will serve as guides for future R&D. If maintenance is a significant factor in pollutant emissions, there will not necessarily be any reduction in emissions unless accompanied either by design of burners requiring less maintenance or education and/or legislation ensuring that the needed maintenance is performed.

Additives and Emulsions

The use of additives appears to offer little promise for reduction of pollutant emissions. However, because no additional equipment is required to fire fuels containing additives, the concept of using additives to reduce emissions continues to hold appeal from the economic viewpoint. Also, the successful use of antiknock additives in automotive engines serves as encouragement for hope in this area.

APCO has examined some 300 additives for distillate fuels in small combustion rigs and has found only a few that appear to cause reduction in emission of smoke.(37,38) Even those additives that cause reduction in emissions have a rather minimal effect on emission levels. Considering that the group of 300 additives tested by APCO probably represents a good cross section of the available additive compounds, it appears unlikely that much further work can be justified for distillate fuels. Additives that have some promise of reducing emissions from combustion of residual fuel oil should be investigated.

Fuel modification as a technique for reducing emissions has not been extensively investigated. However, APCO has sponsored investigations(39-41) aimed at testing water-in-fuel-oil emulsions. The concept is based on earlier work with large individual drops of emulsion that showed that the water inside an oil drop flashed to steam and caused an explosion of the oil drop, or "secondary atomization".(42) The smaller oil droplets resulting from the secondary atomization mix with air and burn more quickly and completely than larger droplets. To date, it has not been proven that atomization is improved when firing water-in-distillate-oil emulsions in practical combustors. However, a one-third reduction of NO_x emission was measured when firing water-in-distillate fuel emulsions(43), possibly because the water caused a reduction of the flame temperature. Emulsions may prove more beneficial when firing residual fuel oil because of the increased difficulty of atomization.

More Comprehensive Emission Data

Currently available emission data on small- and intermediate-size combustion equipment are of marginal value for many purposes including R&D planning and as a measure of current technology. However, the potential usefulness of additional emission measurements and characterization is difficult to evaluate. Measurements should be correlated with design variables, fuels, operating conditions, and service conditions. Data correlated with well-defined operating conditions or design variables will be useful as the basis for design criteria and for relating basic-combustion-process studies to performance of real equipment.

COAL COMBUSTION IN FIXED- AND FLUIDIZED BEDS

Study of trends in fuel use for the "household and commercial sector" of the economy (Figure V-2) readily leads to the conclusion that the use of coal as a fuel by this sector will continue to decrease rapidly. In fact, coal supplies an insignificant portion of the energy utilized for commercial and residential heating. Figure V-1 shows that coal continues to be a significant fuel for industrial steam generation. However, with the increasingly widespread application of limits on the sulfur content of coal used as fuel (and the limited availability of low-sulfur coal), it is likely much of the industrial steam generation currently utilizing coal will shift to gas and/or low-sulfur oil, if available. Therefore, only limited R&D aimed at reducing emissions from small- and intermediate-size coal-fired combustion units appears justified, and this R&D should be directed toward filling specific knowledge gaps.

Three specific areas have been identified where the lack of understanding of the coal-combustion process handicaps emission control by combustion-process modifications.

PNA Formation and Destruction

The total mass of nationwide emissions of PNA is relatively small (CO, HC, and NO_x emissions are over 1000 times greater); however, PNA compounds are considered to be significant pollutants as some of them are carcinogenic.

Over 90 percent of all PNA emissions from energy-conversion combustion processes is attributed to commercial and residential coal-fired sources utilizing fixed-bed combustion. Although small coal-fired units are disappearing from use, their contribution with regard to PNA emissions is so significant that they cannot be ignored.

PNA compounds may be present in the coal itself or may form during the combustion process.(44,45) However, there appears to be no data in the literature which identify PNA as being present in coal. Diehl, DuBruel, and Glenn(46) observed variations in PNA emissions when firing different coals on a pulsating-grate stoker. However, they also observed such variations when operating a pulverized-coal-fired boiler with one fuel and under essentially constant conditions. Consequently, they were not able to relate PNA emissions to coal, and the source of PNA remains uncertain.

The destruction of PNA, as for any other hydrocarbons, should be by oxidation during the combustion process. The literature appears to contain no data which would identify any unique conditions required for oxidation of PNA.(45) However, the fact that PNA compounds are emitted suggests incomplete combustion of these compounds.

Data in both Figure V-5 and Reference 46 indicate that PNA emissions decrease as unit size increases. Larger units provide longer residence times in the flame and, generally, higher average gas temperatures – so that conditions contributing to more nearly complete combustion prevail. Also, fixed-bed combustion units (with poorer mixing) tend to emit larger quantities of PNA than do spreader stokers or pulverized-coal-fired units.

It is possible that, with a better knowledge of how PNA occurs or forms and of the conditions promoting its oxidation, possibilities for modification of the combustion process to reduce PNA emissions could be identified.

Fluidized-Bed Combustion

Fluidized-bed combustion of coal has been proposed as a technique for reducing SO_x emissions from the combustion of high-sulfur coal for steam generation. To accomplish this, limestone is added to the fluidized bed to react with SO_2 and SO_3 as they are liberated from the coal.(37,47)

However, fluidized-bed combustion also has the potential for reducing NO_x emissions from coal combustion because of the reported low temperatures of the fluidized bed. Theoretically, with bed temperatures of about 1800 F, little NO_x would form as the nitrogen-fixation reaction does not proceed rapidly at this temperature. However, Argonne National Laboratories(48) reported relatively high NO_x emission levels for a laboratory fluidized-bed combustor, even with the nitrogen in the air replaced with argon. They attributed these emissions to nitrogen bound in the fuel. However, it is possible that local, high-temperature regions exist within fluidized-bed combustors and that NO_x can form by the nitrogen-fixation reaction in these regions. Additional investigations are needed to answer the question of the source of NO_x in fluidized-bed combustion of coal.

It is likely that most R&D on coal-fired fluidized beds will be directed at central-station power plant application. However, the technology developed in these studies will generally apply to industrial-steam-generation applications as well. One objective of a APCO-sponsored project underway at Westinghouse is to develop a conceptual design for a fluidized bed for this application.

Additional discussion of fluidized-bed technology is contained in Chapter III on Central-Station Power Plants.

Flue-Gas Recirculation

Flue-gas recirculation has been suggested by a number of investigators as a technique for reducing peak temperatures and NO_x formation. Application of flue-gas recirculation to fixed coal beds presents special problems of increasing emissions of particulate due to higher total gas flow and gas velocities through the bed. Also, lower bed temperatures may result in increased emissions of CO and HC due to incomplete combustion.

Experimental studies are needed to determine whether flue-gas recirculation is a practical technique for reducing NO_x emissions from fixed-bed coal combustion units.

SUMMARY OF CURRENT AND RELEVANT COMBUSTION R&D

Table V-8 is a list of R&D projects currently under way which may develop data and/or techniques useful for reducing pollutant emissions from combustion systems for industrial steam generation and commercial and residential heating. NAPCA-sponsored and NAPCA-in-house projects are listed first, followed by projects sponsored by other Federal Government agencies, industrial-sponsored projects, and foreign projects.

Not included in this listing are projects that have proprietary implications and projects from which results will not be generally available. Development projects by burner manufacturers would generally fall into this category and not be listed.

Also not included are projects directed at removing contaminants from fuel by refining processes, projects directed at developing post-combustion control processes, and projects to develop improved instrumentation for measuring air-pollutant emissions. Although R&D in these areas is important relative to the overall pollution-control problem, it is not specifically aimed at reducing emissions by combustion-process or combustion-equipment modification.

Current R&D related to the equipment of concern in this chapter may be classified as follows:

- Understanding the Basic Combustion Process – research aimed at obtaining a better understanding of the physical combustion process including kinetics, mixing, ignition, and other phenomena affecting combustion, either in laboratory rigs or in practical combustors.
- Hardware Development – developmental work aimed at modifying existing combustion equipment or developing new combustion equipment to burn fuels with minimum pollutant emissions.
- Use of Additives and Emulsions – measurements aimed at determining the usefulness of fuel additives or emulsions for emission reduction.
- Determining the Role of Burner Servicing and Maintenance – studies aimed at determining the operating conditions and servicing necessary to minimize emissions.
- Collection of Emission Data – measurements aimed at a more precise determination of the extent and nature of pollutants emitted from various types of combustion equipment, including both additional emission measurements and analytical treatment of available data.

Table V-8. Current Combustion R&D – Industrial Steam Generation and Commercial and Residential Heating

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
V-a	Systems study of nitrogen oxides control methods for stationary sources	NAPCA-DPCE CPA 22-68-55	Esso Res. & Eng. Co. Linden, New Jersey	Dr. W. Bartok	Define the nature and extent of NO_x emissions in U.S. and recommend 5-year R&D program for control	389,307 (Total)
V-b	Selected R&D of nitrogen oxides control for stationary sources	NAPCA-DPCE CPA 70-90	Esso Res. & Eng. Co. Linden, New Jersey	–	Collect additional data on NO_x emissions and investigate the application of control methods on selected sources	363,025 (Total)
V-c	Fossil-fuel combustion equipment	NAPCA-DPCE CPA 22-69-85	Waldon Res. Corp. Cambridge, Mass.	Dr. J. R. Ehrenfeld A. W. Doyle	Correlation of pollutant emissions for various types of combustion equipment	241,902 (FY '69)
V-d	Low emission oil burner	NAPCA-DPCE EHSD 71-Neg 28	Not selected	–	Design and develop a low emission oil-fired residual or small commercial heating unit	–
V-e	Guide to good practice for federal facilities oil burners	NAPCA-OA CPA 22-69-133	Amer. Boiler Manufacturers Asso.	W. Axtman	Recommendations on proper operation for minimum emissions	31,522 (FY '69)
V-f	Studies of preparation and firing of emulsified distillate and residential fuel oils	NAPCA-DPCE PH 86-68-84 Tasks No. 8, 16, 22	Battelle Memorial Inst. Columbus Lab. Columbus, Ohio	R. E. Barrett	Develop techniques for preparing emulsions and demonstrate how they can be fired	
V-g	Conceptual design – fluid-bed combustion – systems	NAPCA-DPCE CPA 70-9	Westinghouse Electric Corp. Res. & Dev. Ctr. Pittsburgh, Penn.	Dr. B. W. Lancaster Dr. D. L. Kearns	Conceptual design of an large industrial coal-fired fluidized-bed combustor (500,000 lb/hr steam)	344,487 (FY '70)
V-h	Models for NO_x formation in stationary combustion processes	NAPCA-DPCE CPA 22-69-44 Task No. 3	Mass. Inst. Tech. Fuels Res. Lab.	H. C. Hottel G. C. Williams A. F. Sarofin	Develop quantitative models for the formation of NO_x in furnaces, influence of varying parameters, and methods to reduce by combustion process modification	28,000 (FY '69)
V-i	Low emission continuous flow combustion for vehicle propulsion	NAPCA-DMVRD CPA 22-69-128	Marquardt Co. Van Nuys, Calif.	C. V. Burkland	Correlation of finite-kinetic-chemical combustion-analysis model with actual combustor tests	97,000 (FY '69)
V-j	Incinerator overfire-air mixing study	NAPCA-DPCE EHSD 71-6	Arthur D. Little Cambridge, Mass.	–	Improve understanding of overfire air and emissions, data may be useful for fixed-bed coal-combustion units	69,738 (FY '71)
V-k	Characteristics of flames causing pollution	NAPCA-DPCE Interagency transfer	Bureau of Mines Pittsburgh, Penn.	J. Grumer M. E. Harris V. R. Rowe E. B. Cook	Correlate emission from small gas burners with design variables	303,000 (Total)

Table V-8. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
V-l	Residential heating project	NAPCA-DPCE	NAPCA-DPCE Cincinnati, Ohio	J. H. Wasser D. P. Howecamp	Identify burner variables and burner designs that minimize emissions	60,000 (FY '69)
V-m	Fuel additive project	NAPCA-DPCE	NAPCA-DPCE Cincinnati, Ohio	G. B. Martin J. H. Wasser	Identify additives that reduce emissions	75,000 (FY '69)
V-n	Distillate fuels research	U. S. Navy	U. S. Navy Civil Eng. Lab. Port Hueneme, Calif.	J. E. Johnson	Improve understanding of heterogeneous combustion	–
V-o	Problems resulting from burning residual fuel in naval boilers	U. S. Navy Navy Ship Systems Command	U. S. Navy Naval Ship Eng. Ctr. Philadelphia, Penn.	W. A. Fritz, Jr.	Eliminate problems of combustion fouling of burner equipment	–
V-p	Secondary combustion in air-augmented rockets	U. S. Navy Naval Material Command	U. S. Navy Naval Weapons Ctr. China Lake, Calif.	J. E. Crump	Understanding of the two-stage combustion process	–
V-q	High-turbulence burner research	NASA	NASA Lewis Res. Ctr. Cleveland, Ohio	W. Roudebush	Improve understanding of the relationships between turbulence and combustion	–
V-r	Combustion-kinetics in an opposed jet burner	NASA	NASA Jet Prop. Lab. Pasadena, Calif.	J. H. Rupe	Improve understanding of the kinetics of combustion systems	–
V-s	Applied chemical kinetics	State of California	UCLA Los Angeles, Calif.	C. Chu	Improve understanding of kinetics of combustion process for opposed-jet diffusion flames	–
V-t	Fundamental study of the combustion of natural gas	American Gas Asso.	Institute of Gas Technology Chicago, Ill.	Dr. R. B. Rosenberg Dr. R. Perfel Dr. R. V. Serauskas	Improve understanding of the combustion process for gaseous fuels	–
V-u	Basic studies of momentum flux, combustion-intensity, and noise in gas-fired combustors	American Gas Asso.	Battelle Memorial Inst. Columbus Lab. Columbus, Ohio	A. A. Putnam	Improve understanding of the combustion process in gas-fired units	–
V-v	Emissions from oil-fired residential and commercial burners	American Petroleum Inst.	Battelle Memorial Inst. Columbus Lab. Columbus, Ohio	D. W. Locklin A. Levy R. B. Engdahl	Field study to measure gaseous and particulate emissions from a range of oil-fired combustion units	–
V-w	Air pollution reduction in heating plants and diesel engines	American Telephone and Telegraph	American Telephone and Telegraph Bell Telephone Lab.	–	Effects of additives on reduction of emissions from oil-fired units	–

Table V-8. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
V-x	Emissions from domestic and commercial space heating units burning gas and oil	American Society of Heating, Refrigerating, and Air Conditioning Engineers	A. D. Little Cambridge, Mass.	John Swanton, Jr.	Survey of literature pertaining to burner adjustment and maintenance and their effect on emission levels	9,500
V-y	Temperature and air distribution in large rectangular incinerator furnaces	Morse Boulger, Inc.	Morse Boulger, Inc. Ansonia, Conn.	M. Dvirka	Data on effect of overfire air jets on smoke and 10 emissions may apply to fixed-bed coal combustion	–
V-z	Blue flame combustion with No. 2 fuel oil	Canadian Government	Canadian Combustion Res. Lab. Ottawa, Ontario, Canada	H. Whaley	Develop low-emission blue-flame oil burner	–
V-aa	Control of pollutant emissions from oil-fired boilers by an additive	Canadian Government	Canadian Combustion Res. Lab. Ottawa, Ontario, Canada	G. K. Lee F. D. Friedrich	Develop and test an additive for control of emissions from oil-fired boilers	–
V-bb	Effects of additives on combustion of fuel oils and reduction of SO_2 in flue gases	–	Royal Tech. H. Sch. Inst. of Inorganic Chemistry Stockholm, Sweden	–	–	–
V-cc	Development and testing of domestic heating appliances with reference to the emission of smoke, unburned hydrocarbons, and other pollutants	–	The Heating and Ventilating Res. Ass'n. Brocknell, England	–	–	–
V-dd	Investigation of soot	Swedish Waters and Air Pollution Res. Lab.	Swedish Waters and Air Pollution Res. Lab. Stockholm, Sweden	C. Brosset B. Steen	Data on microstructure of soot	–
V-ee	Studies of steam boilers and burner control measures to minimize air pollution	– Oslo, Norway	Norwegian Steam Boilers Owners Ass'n. Oslo, Norway	A. Steineger	–	–
V-ff	Studies of the use of additives for the reduction of emissions from vehicles and oil firing	–	Institute for Metallurgy Wullnerstrasse, Germany	–	–	–
V-gg	Investigations of emissions of oil furnaces in regard to offensive odors	Landesamt fur forschung des Landes Nordrhein West falen	Lehrstuhl fur Metallurgie der Kernbrennstoffe und Theorefisch Huttenkunde der Technischen Hochschule Aachen Aachen, Germany	Dr. Ottmar Knacke	Identification of odoriferous compounds emitted by oil furnaces	–

R&D OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Thirteen R&D opportunities have been identified that will fill gaps in technology as applied emission control by combustion modification to industrial steam generation and commercial and residential heating. The R&D opportunities recommended for the 5-Year Plan include work in the following areas:

Combustion Process R&D to Evolve Design Criteria

- Mathematical modeling of the combustion process
- Mixing, turbulence, combustion intensity, and temperature
- Internal recirculation
- External recirculation
- Two-stage combustion
- Fluidized-bed combustion
- PNA formation in fixed coal beds.

Development of New and Improved Equipment Approaches

- Apply design criteria
- Develop low-peak-temperature units.

Investigation of Other Factors

- Transient conditions
- Additives and emulsions (residual fuel oil)
- Maintenance
- More comprehensive emissions factors.

These R&D opportunities range from short tasks (e.g., evaluation of additives and emulsions for reducing emissions from residential fuel oil combustion) to initiating work on long-term tasks (e.g., development of a complete mathematical model of the combustion process in equipment covered in this chapter).

Each of the R&D opportunities suggested involves work that is not likely to be adequately supported by industry or other governmental agencies. APCO has already supported work related to 8 of the 13 proposed R&D opportunities.

In addition to benefiting from the work suggested in these R&D opportunities, combustion technology relating to industrial steam generation and commercial and residential heating is likely to benefit from certain work in other areas. Specifically, these include studies of ash properties from combustion of coal, studies of fluidized-bed combustion, investigations of the effect of fuel-bound nitrogen on NO_x emissions and, indirectly, a number of the fundamental and broadly applicable research opportunities.

The R&D opportunities are described in detail on the following pages and their priorities summarized at the end of this chapter.

R&D Opportunity: V-1 Related to: V-2,3; VIII-13, 18, 19, 22, 25; V-d, k, l, n, q, t, u, z

Experimental Investigation to Develop Design Criteria for Minimum Pollutant Emissions from Small- and Intermediate-Size Combustion Equipment, Considering Mixing, Turbulence, Combustion Intensity, and Furnace Temperature

Technical Objective and Approach

The objective is to define the effect of important combustion variables on pollutant formation in small- and intermediate-size combustion equipment and to develop design criteria for minimizing emissions from these units.

The approach should be to: (1) measure levels of mixing, turbulence, combustion intensity, furnace temperature, and other variables in current designs of combustion equipment, (2) determine optimum levels of each variable using laboratory combustion rigs, and (3) develop criteria for design of low-emission combustion units.

Rationale and Incentive

Although the overall air-fuel ratio of combustion devices may be sufficient to avoid pollutant formation, pollutants do form. A substantial part of the pollutant formation may occur in local pockets that are either fuel rich or too lean to provide satisfactory combustion. These local pockets are the result of incomplete mixing (or unmixedness) of fuel, air, and recirculated combustion products.

Combustion intensity and furnace temperature are major factors in the formation of NO_x and, also, are related to completeness of combustion.

The development of design criteria relating emission formation to important combustor variables, such as: mixing, turbulence, combustion intensity, and furnace temperature, would contribute to the design of low-emission combustion equipment.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $500-$1,700 Recommended 5-year Funding, 1000's: $850

R&D Time Range: 3-10 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	200	200	150	150	150	–

Evaluation

Sources Affected: Oil, Gas, and ½ Coal Industrial Steam Plus Oil and Gas Commercial and Residential

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-30	0-30	0-30	0-30		0-40				–
Expected	18	18	18	18		20				–
Fraction of ECC Emissions Affected	.14	.0014	.010	.044		.071				–
Noncombustion Controls Factor	.2	0	0	0		0				–
Relative Potential Benefit Factor	2.02	0.02	0.18	0.79		1.42				4.43

Implementation Time, years: 5-12 most likely: 7 Relative Implementation Cost: Very Low

Relative Priority Rating: B

An explanation of the evaluation factors used in the priority ranking is contained in Chapter II and Appendix A.

R&D Opportunity: V-2

Related to: V-1, 3; VIII-13, 22, 25; V-d

Experimental Laboratory Investigation of the Effect of Internal Recirculation on Emissions, Demonstration of Optimum Internal Recirculation on Several Small- and Intermediate-Size Combustion Units, and Development of Design Criteria

Technical Objective and Approach

The objective is to define optimum internal recirculation for combustion with low emissions and to determine how it might be achieved in various types of equipment.

The approach initially should involve simple laboratory rigs with configurations not too different from those of practical combustion units. Factors studies for their influence on internal recirculation should include: air momentum (and distribution between primary, secondary, and tertiary air), combustion chamber shape (including edges and abrupt enlargements), and firing intensity. Relations developed in the laboratory studies should be verified through application to several commercial combustion devices. Design criteria should be developed for incorporating optimum internal recirculation into the design of low-emission combustion equipment.

Rationale and Incentive

Internal gas recirculation is known to occur in essentially all combustion devices included within the scope of this study. However, relatively little information is available for quantifying the internal recirculation necessary to achieve combustion with low emissions. A better understanding of internal recirculation would permit the design of combustion units with recirculation levels appropriate for minimum emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$1,200

R&D Time Range: 2-10 years

Recommended 5-year Funding, 1000's: $750

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	150	200	200	100	–

Evaluation

Sources Affected: Oil, Gas, and ½ Coal Industrial Steam Plus Oil and Gas Commercial and Residential

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-30	0-30	0-30	0-30		0-40				–
Expected	15	15	15	15		20				–
Fraction of ECC Emissions Affected	.14	.0014	.010	.044		.071				–
Noncombustion Controls Factor	.2	0	0	0		0				–
Relative Potential Benefit Factor	1.68	0.02	0.15	0.66		1.42				3.93

Implementation Time, years: 5-12 most likely: 7

Relative Implementation Cost: Very Low

Relative Priority Rating: B

R&D Opportunity: V-3 **Related to:** V-1, 2; VIII-1, 4, 6, 8, 9, 13, 17, 19, 22, 25; V-h

Development of Analytical Models to Provide Design Guidance for Small- and Intermediate-Size Combustion Equipment

Technical Objective and Approach

The objective is to develop and improve chemical and physical models of the complete combustion process in small- and intermediate-size combustion equipment. The ultimate objective is to develop a complete chemical and physical model of the combustion process so that emissions can be predicted for proposed combustor designs without the need for experimental data.

The approach should be initiated with careful examination of the literature to include what is known relating to significant phenomena such as atomization, mixing, turbulence, internal and external recirculation, reaction kinetics, heat transfer, and profiles of velocity, temperature, and composition. Models will of necessity be crude at the start because of gaps in knowledge, but as additional information becomes available from laboratory investigations and field measurements, the models should be refined. Where it is recognized that needed information will not be forthcoming from planned research, laboratory investigations should be conducted to generate the needed data.

Rationale and Incentive

There are gaps in the understanding of the basic chemical and physical phenomena associated with combustion in small and intermediate-size combustion equipment. In fact, burner and/or furnace design is largely an art involving cut-and-try development techniques and usually not venturing far from successful past designs.

To minimize the pollutant emissions from combustion equipment, it would be desirable to base new designs on a sound understanding of the combustion phenomena. The development of models of the combustion process and combustion devices would contribute to this understanding. Using these models, pollutant emissions from proposed equipment designs could be evaluated and design alterations made to reduce emissions.

Although the complete physical and chemical models are far in the future, the process of developing the model should be started soon, as it may guide future research by identifying specific gaps in data relating to the combustion process.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-Open
R&D Time Range: 5 years-Open
Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	75	75	125	125	100	100/year

Evaluation

Sources Affected: Oil, Gas, and ½ Coal Industrial Steam, Plus Oil and Gas Commercial and Residential
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-30	0-30	0-30	0-30		0-40				–
Expected	15	15	15	15		20				–
Fraction of ECC Emissions Affected	.12	.0014	.0091	.038		.060				–
Noncombustion Controls Factor	.2	0	0	0		0				–
Relative Potential Benefit Factor	1.44	0.02	0.14	0.57		1.20				3.37

Implementation Time, years: 5-12 **most likely:** 10 **Relative Implementation Cost:** Very Low

Relative Priority Rating: B

R&D Opportunity: V-4 | Related to: V-1, v

Experimental Investigation of the Contribution of Transient Conditions To Emissions from Residential and Small Commercial Combustion Equipment, and Development of Means of Minimizing Emissions During Transient Conditions

Technical Objective and Approach

The objective is to determine the effect on emissions of transient conditions and to devise means to reduce it.

The approach should be to measure emission levels during transient conditions with several types of combustion equipment. Typical operating cycles should be investigated and the portion of pollutant emissions occurring during transient conditions should be established. Subsequently, ways of reducing emissions during transient conditions should be devised. This might involve reducing the severity of the transient phenomena (operating a modulating device in place of an on-off device) or reducing the changes occurring in the combustion chamber during the transient condition (e.g., use a cold-wall combustion chamber for oil furnaces).

Rationale and Incentive

Considerably higher than average pollutant emissions frequently accompany transient conditions (such as the start and end of a firing cycle) for small- and intermediate-size combustion equipment. This is particularly true for startup of units that operate with hot firebox walls (such as domestic oil furnaces), as the walls must heat to operating temperature before emissions are stabilized. Also, a few seconds may be required to establish gas-movement patterns in fireboxes and mixing may be poor during this period.

It would be desirable to determine what portion of total emissions occurs during transient conditions and, if this portion is significant, to determine ways of avoiding high emissions during these periods.

Estimated R&D Cost & Time

R&D Cost Range, 1,000's: $550-$1,300

R&D Time Range: 3-8 years

Recommended 5-year Funding, 1000's: $775

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	175	150	125	125	–

Evaluation

Sources Affected: Oil and Gas Commercial and Residential

Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-10	0-10	0-10			0-5				–
Expected	5	5	5			3				–
Fraction of ECC Emissions Affected	.055	.0005	.003			.032				–
Noncombustion Controls Factor	0	0	0			0				–
Relative Potential Benefit Factor	0.28	0	0.02			0.10				0.40

Implementation Time, years: 4-10 most likely: 7

Relative Implementation Cost: Medium

Relative Priority Rating: E

R&D Opportunity: V-5 Related to: VIII-6, 10, 11, 12

Experimental Investigation of the Mechanisms by which PNA is Formed and Destroyed during the Combustion of Coal on Fixed Beds and Development of Design Criteria to Minimize PNA Emissions with Demonstration on Boiler Units

Technical Objective and Approach

The objective is to determine and control the mechanism of PNA formation and destruction in coal-burning combustion equipment.

The approach should include investigation of both the pyrolysis-phase and the gas-phase combustion of fuel-bed burning. Effects of bed temperature profile, local air-fuel ratio, bed characteristics, fuel characteristics, and other factors should be experimentally determined using laboratory combustors and making measurements on operating equipment.

After the mechanism of PNA emission is established, the results should be incorporated into guidelines for the design of practical units with low PNA output.

Rationale and Incentive

The single major source of the total national PNA emissions is the burning of coal in small- to intermediate-size combustion devices. Although the number of small- and intermediate-size coal-fired combustion sources is decreasing, this source will continue to account for the largest portion of PNA emissions. Therefore, it is important to determine how these emissions can be reduced.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $400-$1,000

Recommended 5-year Funding, 1000's: $600*

R&D Time Range: 2-8 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	150	150	150	150	–	–

Evaluation

Sources Affected: ½ Coal Industrial Steam Plus Coal Commercial and Residential

Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range				0-90						–
Expected				48						–
Fraction of ECC Emissions Affected				0.36						–
Noncombustion Controls Factor				0						–
Relative Potential Benefit Factor				17.28						17.28

Implementation Time, years: 4-10 **most likely:** 6

Relative Implementation Cost: Very Low

Relative Priority Rating: C

Although the ranking procedure would assign this R&D opportunity a Relative Priority Rating in the A category, it has judgementally been reduced to Rating C, as it is believed that the major sources of PNA emissions are not ECC sources and, therefore, are not included in this study.

R&D Opportunity: V-6 **Related to: V-7; VIII-27; V-a, b, h, p**

Experimental Investigation of the Application of Flue-Gas Recirculation and Two-Stage Combustion (and in combination) to Residential and Small Commercial Oil and Gas Burners with Demonstration Prototypes

Technical Objective and Approach

The objective is to solve problems associated with the applications of flue-gas recirculation and two-stage combustion to residential and small commercial combustion equipment.

The approach should include laboratory investigations of recirculation to determine: (1) the necessary level of recirculation for various sizes and types of burners, for various firing rates, and for various fuels; (2) the optimum temperature of recirculated flue gas and the optimum point of injection; (3) means for supplying the energy necessary to accomplish the flue-gas movement associated with recirculation; and (4) methods for avoiding corrosion of the recirculation loop. For units operated over a range of firing rates, it will be necessary to consider controls to vary the quanity of recirculated gas as a function of firing rates. Above all, recirculation for emission reduction should not reduce performance of the unit in such areas as flame stability and ignitability.

Laboratory investigations of two-stage combustion should determine: (1) methods to avoid impractically long residence times, (2) methods to avoid the formation of smoke or intermediates difficult to oxidize, (3) the effect of local reducing conditions on corrosion, and (4) means to ensure complete mixing of the secondary air with the products of the primary combustion to complete combustion.

After laboratory work has been completed, demonstration prototypes should be constructed.

Rationale and Incentive

Recirculation of flue gas and two-stage combustion are promising techniques for reducing peak combustion-zone temperatures and, therefore, reducing NO_x emissions without sacrificing unit efficiency. Several studies have shown that recirculation and two-stage combustion can reduce NO_x emissions. In fact, for small-size combustion equipment, flue-gas recirculation and/or two-stage combustion may be the only practical techniques, from an economic standpoint, for reducing NO_x emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$1,000 Recommended 5-year Funding, 1000's: $600*

R&D Time Range: 2-6 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's		200	200	200	–	–	–

Evaluation

Sources Affected: Oil and Gas Commercial and Residential

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-50					20-50				–
Expected	28					35				–
Fraction of ECC Emissions Affected	.060					.040				–
Noncombustion Controls Factor	0					0				–
Relative Potential Benefit Factor	1.68					1.40				3.08

Implementation Time, years: 4-8 most likely: 5 Relative Implementation Cost: Medium

Relative Priority Rating: D

R&D Opportunity: V-7

Related to: III-2, 3, 4; V-6; VIII-27; V-a, b, h, p

Experimental Investigation of the Application of Flue-Gas Recirculation and Two-Stage Combustion (and in combination) to Typical Oil- and Gas-Fired Industrial Package Boilers With One Demonstration Prototype

Technical Objective and Approach

The objective is to solve problems associated with the application of flue-gas recirculation and two-stage combustion to oil- and gas-fired industrial package boilers.

The approach should include laboratory investigations of recirculation to determine: (1) the necessary level of recirculation for various sizes and types of burners, for various firing rates, and for various fuels; (2) the optimum temperature of recirculated flue gas and the optimum point of injection; (3) means for supplying the energy necessary to accomplish the flue-gas movement associated with recirculation; and (4) methods for avoiding corrosion of the recirculation loop. For units operated over a range of firing rates, it will be necessary to consider controls to vary the quantity of recirculated gas as a function of firing rates. Above all, recirculation for emission reduction should not reduce performance of the unit in such areas as flame stability and ignitability.

Laboratory investigations of two-stage combustion should determine: (1) methods to avoid impractically long residence times, (2) methods to avoid the formation of smoke or intermediates difficult to oxidize, (3) the effect of local reducing conditions on corrosion, and (4) means to ensure complete mixing of the secondary air with the products of the primary combustion to complete combustion.

After laboratory work has been completed, a demonstration prototype should be constructed.

Rationale and Incentive

Recirculation of flue gas and two-stage combustion are promising techniques for reducing peak combustion-zone temperatures and, therefore, reducing NO_x emissions without sacrificing unit efficiency. Several studies have shown that recirculation and two-stage combustion can reduce NO_x emissions. In fact, for oil- and gas-fired industrial package boilers, flue-gas recirculation and/or two-stage combustion may be the only practical techniques, from an economic standpoint, for reducing NO_x emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $400-$1,300
R&D Time Range: 2-5 years

Recommended 5-year Funding, 1000's: $650*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	250	200	200	–	–	–

Evaluation

Sources Affected: Oil and Gas Industrial Steam
Relative Potential Benefit (overall rating): Medium Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-50					20-70				–
Expected	28					48				–
Fraction of ECC Emissions Affected	.038					.034				–
Noncombustion Controls Factor	0					0				–
Relative Potential Benefit Factor	1.06					1.63				2.69

Implementation Time, years: 4-8 most likely: 5

Relative Implementation Cost: Low

Relative Priority Rating: C

R&D Opportunity: V-8

Related to: V-6, 7; VIII-20, 27; V-a, b, h

Experimental Laboratory Investigation of the Application of Flue-Gas Recirculation to Fixed-Bed Coal Combustion with Laboratory Demonstration

Technical Objective and Approach

The objective is to solve problems associated with the applications of flue-gas recirculation to fixed-bed coal-combustion equipment.

The approach should include laboratory investigations to determine: (1) the necessary level of recirculation for various sizes and types of beds for various firing rates, and for various fuels; (2) the optimum temperature of recirculated flue gas and the optimum point of injection to maintain good combustion and reduce NO_x formation; (3) the energy necessary to accomplish the flue-gas movement associated with recirculation; and (4) means for preventing corrosion of the recirculation loop. For units operated over a range of firing rates, it will be necessary to consider controls to vary the quantity of recirculated gas as a function of firing rates. Above all, recirculation for emission reduction should not reduce performance of the unit in such areas as flame stability and ignitability. Laboatory equipment should be developed for demonstration purposes.

Rationale and Incentive

Recirculation of flue gas is a promising technique for reducing peak combustion-zone temperatures and, therefore, reducing NO_x emissions without sacrificing unit efficiency. In fact, for small- and intermediate-sized fixed-bed combustion equipment, flue-gas recirculation may be the only practical technique, from an economic standpoint, for reducing NO_x emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $500-$1,500

Recommended 5-year Funding, 1000's: $1,100*

R&D Time Range: 2-6 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	200	300	300	300	–	–

Evaluation

Sources Affected: ½ Coal Industrial Steam

Relative Potential Benefit (overall rating): Very Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						20-70				–
Expected						35				–
Fraction of ECC Emissions Affected						.011				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.38				0.38

Implementation Time, years: 4-9 most likely: 6

Relative Implementation Cost: Low

Relative Priority Rating: E

R&D Opportunity: V-9 | **Related to:** III-6, 7; V-g

Conceptual Design and Supporting Experimental Investigations to Guide the Application of Fluidized-Bed Combustion of Coal to Industrial Steam Generation

Technical Objective and Approach

The objective is to develop fluidized-bed combustion units for industrial steam generation.

The approach should include conceptual studies to establish equipment configurations and economical feasibility and experimental studies are needed to resolve technical questions and develop design criteria. Particularly needed are further studies of the emission of NO_x from such combustion systems, including the possible contribution of chemically-bound nitrogen in the coal, and studies to determine how emissions of HC, CO, and PNA can be avoided.

Rationale and Incentive

Fluidized-bed combustion of coal offers the prospect of reduction of NO_x emissions due to lower combustion temperatures as well as the removal of sulfur oxides by reaction with limestone in the bed. Although fluidized-bed demonstrations to date have been with units many times smaller than those necessary for industrial steam generation, the scale-up to industrial steam generation is much less than for the proposed central-station power plant applications.

Studies by the Argonne National Laboratory have indicated that NO_x emissions from fluidized-bed combustion of coal are not low. Based on experiments with argon substituted for the nitrogen in air, they concluded that the NO_x formed from the nitrogen in the fuel. However, these tests were not conclusive as local high-temperature regions in the fuel bed might have produced the same NO_x levels. Therefore, it will be necessary to determine experimentally whether or not fluidized-bed combustion produces low NO_x emissions and, if it does not, how the process might be controlled to produce low emissions.

NAPCA is currently sponsoring a conceptual study of an industrial-size fluidized bed and several experimental studies.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $600-$2,000
R&D Time Range: 3-10 years

Recommended 5-year Funding, 1000's: $1,050

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	250	250	250	150	150	–

Evaluation

Sources Affected: Coal Industrial Steam
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						30-75		50-95	0-50	–
Expected						44		74	15	–
Fraction of ECC Emissions Affected						.018		.042	.062	–
Noncombustion Controls Factor						0		0	.5	–
Relative Potential Benefit Factor						0.79		3.11	0.46	4.36

Implementation Time, years: 6-12 **most likely:** 8

Relative Implementation Cost: Medium

Relative Priority Rating: D

R&D Opportunity: V-10

Experimental Investigation to Develop Low-Peak-Temperature Residential Heating Units to Reduce NO_x Emissions

Technical Objective and Approach

The objective is to develop low-peak-temperature gas- and oil-fired heating units to reduce NO_x emissions from residential space heating equipment.

The approach should include investigations aimed at developing low-peak-temperature domestic heating units which achieve acceptable thermal efficiencies with low-temperature flue gas and do not increase emissions of incompletely burned fuel or CO.

One type of unit that should be studied is the catalytic gas burner with peak temperatures of 1800 F to 2000 F. Other approaches include radiant burners and burners that operate at high air/fuel ratios.

Rationale and Incentive

Flue-gas cleanup processes and extensive modifications of combustion equipment (such as two-stage combustion) will quite likely be uneconomical for small space-heating units. Furthermore, current combustion technology indicates that low NO_x emissions can be achieved only by burning at low temperatures. Therefore, it is desirable to investigate the development of low-temperature heating units.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $250-$900

R&D Time Range: 2-8 years

Recommended 5-year Funding, 1000's: $475

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	75	100	150	150	–	–

Evaluation

Sources Affected: Oil and Gas Commercial and Residential

Relative Potential Benefit (overall rating): Medium Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						40-90				–
Expected						75				–
Fraction of ECC Emissions Affected						.034				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						2.55				2.55

Implementation Time, years: 3-10 **most likely:** 6

Relative Implementation Cost: Low

Relative Priority Rating: C

R&D Opportunity: V-11 Related to: VIII-18; V-f, m, aa, bb, ff

Experimental Investigation of Additives and Emulsions for Reducing Emissions from Residual Fuel-Oil Combustion

Technical Objective and Approach

The objective is to determine whether either atomization, combustion, or emissions are favorably affected by: (1) additives in the oil or (2) firing water-in-oil emulsions.

The approach should include investigation of the few additives that have shown promise for reducing emissions from distillate oil combustion and of additives for which some sound evidence of emission reduction is available. The emulsion concept should be developed to the point where it can be determined whether emulsification of fuel oil improves atomization and combustion and, thereby, lowers emission levels (beyond the effect of the water on lowering flame temperature).

Studies should be carried out with laboratory rigs that provide combustion conditions not too different from those characteristic of practical equipment. Atomization studies could be conducted in a freeze-out chamber or by holographic techniques.

Rationale and Incentive

The use of fuel additives to improve combustion and, therefore, to reduce emissions at low cost is appealing. However, extensive tests by NAPCA using additives in distillate fuel oil have not shown substantial reductions in emissions. Because residual fuel oil is more difficult to atomize and burn than distillate fuel oil, additives might be expected to show a greater effect on residual oil combustion than on distillate combustion.

It might even be feasible to alter the physical properties affecting atomization characteristics of fuel oils by incorporating additives in the fuel oil. Better atomization will produce improved combustion and, consequently, lower emissions.

The emulsion concept for obtaining improved atomization appears interesting. NAPCA investigation of firing water-in-distillate fuel-oil emulsions indicated there was a 1/3 reduction in NO_x emissions. The use of emulsions in units firing residual fuel oil may prove more beneficial because of the inherent difficulty in buring residual oil.

One or both of these techniques may be useful in reducing emissions from small and intermediate-size combustion equipment.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$300 **Recommended 5-year Funding, 1000's:** $175

R&D Time Range: 1-3 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	100	75	–	–	–	–

Evaluation

Sources Affected: Oil Power Plants, Industrial Steam, and Commercial and Residential

Relative Potential Benefit (overall rating): Medium Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-40	0-20	0-20			0-50				–
Expected	20	10	10			22				–
Fraction of ECC Emissions Affected	.059	.0008	.0056			.054				–
Noncombustion Controls Factor	0	0	0			0				–
Relative Potential Benefit Factor	1.18	0.01	0.06			1.19				2.44

Implementation Time, years: 2-4 **most likely:** 3 **Relative Implementation Cost:** Medium

Relative Priority Rating: D

R&D Opportunity: V-12

Related to: V-e, o, v, x

Experimental Investigation of the Effect of Burner Maintenance on Emissions from Commercial and Residential Oil Burners, and Development of Design Criteria to Minimize Performance Deterioration

Technical Objective and Approach

The objective is to (1) determine the minimum maintenance required to keep various types of oil burners operating at the lowest possible emission levels, and (2) determine which components tend to require maintenance to prevent pollutant emissions from increasing.

The approach should include field measurements of emissions from a large number of oil burners, adjusting or servicing these units to return them to good operating condition, and annual or semiannual emission measurements to determine deterioration of performance with time. Results of this study should include: (1) development of rècommendations for maintenance work and intervals, and (2) guidelines for the design of burners that require minimum maintenance to operate at low emission levels for long time periods.

Rationale and Incentive

Lack of maintenance and/or servicing is known to result in increased smoke levels, even with well-designed oil-burning equipment. A similar relation might be found for other pollutants.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$400

Recommended 5-year Funding, 1000's: $300

R&D Time Range: 2-4 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	150	75	75	–	–	–

Evaluation

Sources Affected: Oil Commercial and Residential

Relative Potential Benefit (overall rating): Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-30	0-30	0-30							–
Expected	15	15	15							–
Fraction of ECC Emissions Affected	.031	.0005	.0032							–
Noncombustion Controls Factor	0	0	0							–
Relative Potential Benefit Factor	0.47	0.01	0.05							0.53

Implementation Time, years: 4-8 most likely: 6

Relative Implementation Cost: Low

Relative Priority Rating: D

R&D Opportunity: V-13 Related to: V-4; V-b, l, v

Measurement of Emissions from Various Types of Industrial, Commercial, and Residential Combustion Equipment to Develop More Comprehensive Emission Factors and to Provide Design Guidance

Technical Objective and Approach

The objective is to upgrade the knowledge of emissions from various types of combustion equipment firing various fuels under different conditions.

The approach should consist of field measurements of emissions from various combustion units. A sufficiently large number of units should be included so as to enable both average emission levels and ranges to be established. As there are likely quite large differences in emission levels from different designs of equipment for similar applications, data should be obtained for different types of units and not general categories such as "domestic oil burners".

Rationale and Incentive

Reliable emission data are lacking for some kinds of equipment, fuels, and operating conditions; also, there are serious questions as to the accuracy of older data. Accurate data would be useful for emission inventories, future planning, identifying types of combustion equipment that emit particularly large quantities of pollutants, and providing guidelines for other research efforts.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$600

R&D Time Range: 3-6 years

Recommended 5-year Funding, 1000's: $480

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	150	150	60	60	60	–

Evaluation

Although funding this R&D Opportunity will not contribute directly to reducing emissions, it will provide data useful to other R&D. A judgmental evaluation was used to assign the Relative Priority Rating to this R&D Opportunity.

Relative Priority Rating: C

R&D Opportunity: V-New Concepts

Provision for Exploring New Concepts and New R&D Opportunities that Evolve from the Program, Accelerating Promising R&D, or Conducting Demonstrations of Promising Concepts for Reducing Emissions from Combustion Equipment used for Industrial Steam Generation and for Space and Water Heating by Combustion Modification

Technical Objective and Approach

The objective is to provide for long-range flexibility in the R&D program to enable APCO to take advantage of opportunities that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the R&D program to explore the feasibility of new and novel concepts and to accelerate research, development, and demonstration of promising concepts for reducing emissions by combustion-process modification. Worthwhile ideas for combustion-process modification to reduce emissions from combustion equipment used for space and water heating and industrial steam generation might originate as the result of novel design concepts or through in-depth understanding derived from well-planned R&D. The merits of specific R&D opportunities should be decided by evaluating the particular concepts as they evolve.

Rationale and Incentive

The design of combustion equipment for industrial steam generation will probably benefit from combustion developments for central-station power plants. Refinements and new ideas relating to combustion processes for generating steam will likely see initial application in power plants because of their much greater share of total emissions. However, techniques that prove beneficial for reducing power-plant emissions may also have application to industrial steam generation.

The design of future residential and commercial heat equipment will be influenced by such objectives as low noise level, high combustion intensity (affecting equipment size), and demands for modulation rather than on-off controls. It is possible that the design of equipment to achieve these objectives may provide opportunities for emission reduction by incorporating features such as improved atomization and mixing, variable-area air inlets, recirculation, and control of flame luminosity.

Recommended Funding Allocation

	71	72	73	74	75	
Funding by Fiscal Year, $1000's	–	150	200	250	250	5-year Funding, 1000's: $ 850

Evaluation

This R&D Opportunity is unranked. Potential benefit, implementation time, implementation cost, and funding level for each specific opportunity must be evaluated when the opportunity is identified. The suggested funding level anticipates effort on several R&D opportunities.

Relative Priority Rating: N

TABLE V-9. SUMMARY BY PRIORITIES

INDUSTRIAL STEAM GENERATION AND COMMERCIAL AND RESIDENTIAL HEATING

Relative Priority Rating		R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
B	V-1	Experimental Investigation to Develop **Design Criteria** for Minimum Pollutant Emissions from Small- and Intermediate-Size Combustion Equipment, Considering **Mixing, Turbulence, Combustion Intensity**, and **Furnace Temperature**	X	200	200	150	150	150	850	–
B	V-2	Experimental Laboratory Investigation of the Effect of **Internal Recirculation** on Emissions, Demonstration of Optimum Internal Recirculation on Several Small- and Intermediate-Size Combustion Units, and Development of **Design Criteria**	–	100	150	200	200	100	750	–
B	V-3	Development of **Analytical Models to Provide Design Guidance** for small- and Intermediate-Size Combustion Equipment	–	75	75	125	125	100	500	100/yr
		Totals, Priority B		375	425	475	475	350	2,100	
C	V-5	Experimental Investigation of the Mechanisms by which PNA is Formed and Destroyed during the Combustion of Coal on **Fixed Beds** and Development of **Design Criteria to Minimize PNA** Emissions with Demonstrations on Boiler Units	X	150	150	150	150	–	600*	–
C	V-7	Experimental Investigation of the Application of **Flue-Gas Recirculation** and **2-Stage Combustion** (and in combination) to Typical Oil- and Gas-Fired Industrial **Package Boilers** with one Demonstration Prototype	X	250	200	200	–	–	650*	–

TABLE V-9. (Continued)

Relative Priority Rating	R&D Opportunity		Current NAPCA R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
C	V-10	Experimental Investigation to Develop **Low-Peak-Temperature Residential Heating Units to Reduce NO_x** Emissions	–	75	100	150	150	–	475	–
C	V-13	Measurement of Emissions from Various Types of Industrial, Commercial, and Residential Combustion Equipment to Develop **More Comprehensive Emission Factors** and to Provide **Design Guidance**	X	150	150	60	60	60	480	–
		Totals, Priority C		625	600	560	360	60	2,205	
D	V-6	Experimental Investigation of the Application of **Flue-Gas Recirculation** and **2-Stage Combustion** (and in combination) to **Residential and Small-Commercial Oil & Gas Burners** with Demonstration Prototypes	X	200	200	200	–	–	600*	–
D	V-9	Conceptual Design and Supporting Experimental Investigations to Guide the Application of **Fluidized-Bed Combustion** of Coal to **Industrial Steam Generation**	X	250	250	250	150	150	1,050	–
D	V-11	Experimental Investigation of **Additives and Emulsions** for Reducing Emissions from **Residual Fuel-Oil** Combustion	X	100	75	–	–	–	175	–
D	V-12	Experimental Investigation of the Effect of Burner **Maintenance** on Emissions from Commercial and Residential Oil Burners and Development of **Design Criteria to Minimize Performance Deterioration**	–	150	75	75	–	–	300	–
		Totals, Priority D		700	600	525	150	150	2,125	

TABLE V-9. (Continued)

Relative Priority Rating		R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
E	V-4	Experimental Investigation of the Contribution of **Transient Conditions** to Emissions from Residential and Small Commercial Combustion Equipment, and Development of Means of Minimizing Emissions during Transient Conditions	X	200	175	150	125	125	775	–
E	V-8	Experimental Laboratory Investigation of the Application of **Flue-Gas Recirculation** to **Fixed-Bed Coal Combustion** with Laboratory Demonstration	–	200	300	300	300	–	1,100*	–
		Totals, Priority E		400	475	450	425	125	1,875	
N	V-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Combustion Equipment used for Industrial Steam Generation and for Space and Water Heating by Combustion Modification	–	–	150	200	250	250	850	–
		Totals, All Priorities		2,100	2,250	2,210	1,660	935	9,155	

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Chapter VI

CONTINUOUS-COMBUSTION ENGINES – GAS TURBINES AND EXTERNAL-COMBUSTION ENGINES

Herbert R. Hazard

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CHAPTER VI

CONTINUOUS-COMBUSTION ENGINES – GAS TURBINES AND EXTERNAL-COMBUSTION ENGINES

SCOPE OF CHAPTER AND BACKGROUND

This chapter is concerned with combustion in continuous-combustion engines, including gas turbines and external-combustion engines. External-combustion engines of principal interest are the automotive Rankine-cycle engine and the automotive Stirling-cycle engine.

At the present time, gas-turbine engines are a small source of pollutants because of their relatively clean exhaust and their relatively limited total installed power level. However, as the application of gas turbines expands in the future, and the emissions of pollutants from other sources are reduced by future controls, it is expected that emissions from gas turbines will grow in importance.

The Rankine-cycle automotive engine, the Stirling-cycle automotive engine, and the automotive gas turbine are of great interest because of their potential capability of replacing the present automotive gasoline engine and reducing significantly the emissions from automobiles.

Table VI-1 shows the percentages of total national emissions from energy-conversion combustion (ECC) processes contributed by aircraft gas turbines and industrial gas turbines. Total emission levels are below two percent for all pollutants.

Table VI-1. Emissions From Aircraft and Industrial Gas Turbines*

	Contribution to Nationwide ECC Emissions, percent		
Pollutant	Aircraft Gas Turbines	Stationary Gas Turbines	Total, All Gas Turbines
Products of Incomplete Combustion			
Combustible Particulate	<1	<1	1
CO	1	nil	1
Gaseous HC	1	nil	1
PNA	nil	nil	nil
NO_x	<1	<1	1
Combustion-Improving Additives			
Lead	nil	nil	nil
Fuel Contaminants			
SO_x	nil	nil	nil
Ash (Noncombustible Particulate)	nil	nil	<1

*Derived from data in Table II-1 and References 1 and 3.

POLLUTANTS OF PRINCIPAL CONCERN

Aircraft Gas Turbines

The pollutants of greatest interest for aircraft in terminals are CO, HC, and odor, which are emitted in substantial quantities during idle and taxi operations. During approach and takeoff, smoke is of principal interest because of its visibility, although its emission on a weight basis is negligible. During high-altitude cruise, the principal pollutants are combustible particulates (invisible smoke) and NO_x. Sulfur is present in small quantities in the fuel (0.1 to 0.3 percent), and SO_2 is emitted in relatively small quantities.

Stationary Gas Turbines

The emissions from stationary gas turbines when operating at high power levels are combustible particulate and NO_x, and emission levels are similar to those from aircraft gas turbines at high power levels. However, industrial turbines are not usually operated for extended periods at low power levels and, thus, do not contribute significant quantities of CO, HC, and odor. Although most industrial units burn natural gas as fuel, many are suitable for burning high-sulfur distillates or residual fuel oils should the need arise.

Automotive Gas Turbines

At the present time, automotive gas turbines can meet proposed 1980 automotive emission standards, except for NO_x. Emission levels of NO_x from these gas turbines are about 4 times the proposed standards.

Rankine-Cycle Automotive Engines

For continuous, full-load firing conditions, experimental Rankine-cycle burners have demonstrated the ability to meet proposed 1980 emission standards. However, a very large turndown ratio is required for such burners, and part-load operation with acceptable emission levels has not been demonstrated.

Stirling-Cycle Automotive Engines

The combustors utilized in Stirling-cycle engines are quite similar to those used in gas turbines, and emissions are similarly low. However, the turn-down problem is more critical, since the entire turn-down range of the burner occurs at fixed (ambient) pressure. Critical pollutants have not yet been delineated for automotive Stirling-cycle engines, but it is expected that NO_x will be of greatest concern at high power levels and that CO and HC will be of greatest concern at idle and low power levels.

GAS TURBINES

GAS-TURBINE APPLICATIONS

Covered in this section are applications of gas turbines for aircraft propulsion, industrial uses, and automotive power plants.

Aircraft Gas Turbines

Historically, the gas turbine was first developed for propulsion of military aircraft. In 1959 the first turbojet transport, the Boeing 707, was introduced. Within the short span of 10 years the turbojet, the turboprop and, later, the turbofan engine replaced all piston engines in U.S. airline service, with greatly reduced operating cost and improved passenger acceptance.

At the present time about 2000 first-line transport aircraft are in service, and they emit about 0.25 percent of nationwide emissions from ECC sources. The average utilization of a commercial transport is about 10 hours per day.

About half of all jet aircraft fuel is consumed by military aircraft.(1) Although they outnumber commercial aircraft, their utilization factor is lower. It is estimated that the pollutant emissions from military aircraft are equal to those for civil aircraft, in proportion to fuel consumption for each.

Industrial Gas Turbines

The success of aircraft gas turbines led to the development of industrial gas turbines based on aircraft technology. In general, the heavy-duty industrial unit is designed for longer life and has larger combustors suitable for heavier fuels than an aircraft unit, often including selected grades of No. 6 fuel oil. A more recent development is the direct application of aircraft turbojet engines as gas generators to drive heavy-duty power turbines for pipe-line pumping and for generation of peaking power for utilities. These aircraft engines are highly developed and very efficient, and they can be started and brought to full power within 5 minutes. Furthermore, a complete gas generator can be replaced in as little as 4 hours and the old unit moved to an overhaul shop, minimizing maintenance costs.

At the present time, about 50,000,000 hp of gas-turbine capacity is installed in the U.S. in industrial and utilities service(3), of which half of the total power is generated by units of 20,000 hp or larger. The fuel consumption of these industrial units is estimated to be about equal to that of aircraft units.

Automotive Gas Turbines

Automotive gas turbines have been under continuous development for more than 20 years, but none is yet in production as a commercial engine. Present efforts of Ford and General Motors are directed toward production of a heavy-duty engine for trucks and buses. In this application, the gas turbine is competitive with the diesel engine. It has the potential advantages over the diesel of longer life, less maintenance, lighter weight, and smaller size. Emission levels of pollutants should be considerably lower than those of either diesel engines or gasoline engines, and cost should be similar to that of diesel engines.

The greatest potential application for the gas turbine in the reduction of pollution levels, however, is as a passenger-car engine. The Chrysler Corporation undertook such a development in the years between 1950 and 1968, and solved many technical and production problems in preparing for introduction of such an engine. However, costs were not competitive with those of current gasoline engines, and the development effort was reduced to a low level following a nationwide field trial utilizing 50 automobiles.

The principal obstacle to application of the gas turbine to passenger automobiles is the mismatch of passenger-car power requirements and gas-turbine power characteristics. The passenger car operates most of the time at very low power levels, with occasional operation at high power levels. Thus, it requires an engine that is efficient at low power levels and at idle, as is the gasoline engine. The gas turbine is most efficient at maximum power, and loses efficiency rapidly at power levels below 1/4 power. The idling fuel consumption of a typical automotive gas turbine is 13 lb per hr(4) compared with only 2 lb per hr for a gasoline engine. While it is technically possible to apply gas turbines to automobiles today, with much reduced emission of pollutants, the fuel consumed by automobiles would increase somewhat. (The Chrysler field trials indicated that average driving cost, using a cheaper fuel, was about the same as for a standard auto, although fuel consumption for the gas turbine car was slightly higher.)

EMISSION CHARACTERISTICS OF PRESENT GAS TURBINES

Aircraft Gas Turbines

The aircraft gas-turbine combustor operates over a wide range of combustion conditions with different emissions over different parts of the operating range. Fuel-air ratio in the combustor can vary over a 4:1 range, between full power and idle; the combustor pressure can vary over a 10:1 range; and fuel flow can vary over a 100:1 range.

Figure VI-1 illustrates the relation between combustor fuel-air ratio, pressure, engine speed, and altitude for a typical engine having a pressure ratio of 5.(5) Combustors must operate satisfactorily at all conditions within such a performance envelope, and must relight satisfactorily under altitude windmilling conditions. Most of the recent engines have higher combustor pressures, but operating characteristics are similar.

Table VI-2 summarizes the emission characteristics of a typical turbofan engine used widely in transport aircraft.(6) This particular engine is fitted with the most recent design of combustor and emits no visible smoke. The values for carbon emission for a smoking engine would be about twice those shown in Table VI-2, and NO_x emissions would be somewhat lower. Combustors that emit no visible smoke have been developed by the three major manufacturers of large aircraft turbine engines.(7,8,9)

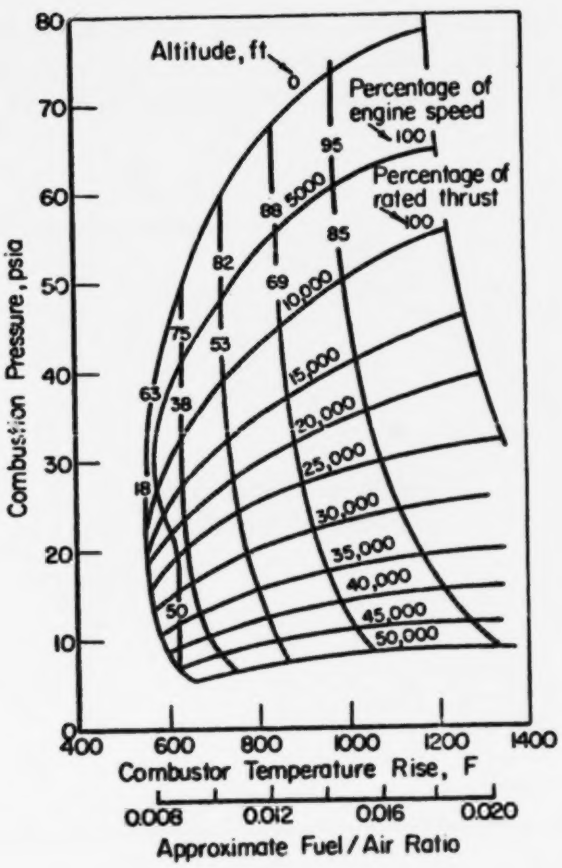


Figure VI-1. Typical Combustor Operating Characteristics(5)

Table VI-2. Emissions From a Typical Turbofan Aircraft Engine With Low-Smoke Combustors*

Throttle Position		Idle	Approach	Cruise	Takeoff
Thrust, lb		**525**	**5,100**	**11,500**	**13,600**
Fuel flow, lb/hr		780	3,196	6,740	8,330
Fuel-air ratio		0.0074	0.0109	0.0148	0.0176
Dry carbon:	ppm	–	–	–	–
	lb/hr	0.34	1.53	2.38	3.12
	lb/lb fuel	0.00044	0.00048	0.00035	0.00038
CO:	ppm	590	52	17.2	15
	lb/hr	60.26	14.8	7.6	6.9
	lb/lb fuel	0.07726	0.00462	0.00113	0.00083
HC:	ppm as CH_4	200	3.7	1.8	1.3
	lb/hr	11.62	0.61	0.39	0.32
	lb/lb fuel	0.01492	0.00019	0.00006	0.00004
NO_x:	ppm	7.4	23.2	67.6	98.0
	lb/hr	0.75	6.58	29.72	44.98
	lb/lb fuel	0.00097	0.00206	0.00441	0.00540

*Courtesy Pratt and Whitney Aircraft.

Figure VI-2 illustrates the relation between combustion efficiency and engine power setting for typical turbojet engines. The inefficiency, or loss, is in the form of CO and unburned HC, and this accounts for the odor associated with ground operation of jet aircraft.

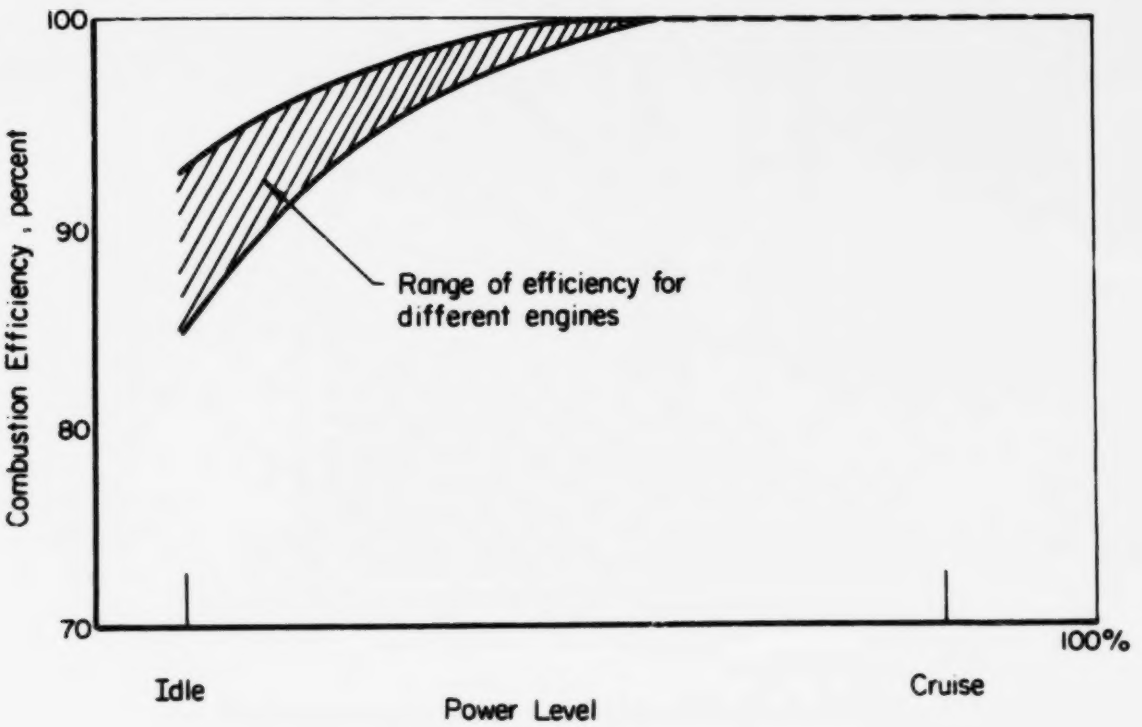


Figure VI-2. Relation of Combustion Efficiency to Power Level for Turbojet and Turbofan Aircraft Engines

Industrial Gas Turbines

Industrial gas turbines have emission characteristics similar to those of aircraft gas turbines. In fact, many are aircraft-engine adaptations. However, heavy-duty gas turbines often utilize air atomization for improved low-load operation with No. 2 fuel oil or heavier fuel, and they seldom operate at low loads. Accordingly, the principal emissions of interest are NO_x and smoke. Manufacturers of large gas turbines have recently developed heavy-duty combustors that produce no visible smoke, following practice pioneered for aircraft gas turbines.(10,11)

The most widely burned fuel for industrial gas turbines is natural gas, followed by distillate fuel oil. Only minor amounts of other fuels are burned, including blast-furnace gas, coke-oven gas, naptha, and residual fuel oil. Except for residual fuel oil, these fuels are very low in sulfur, and emissions of SO_2 are very small.

Automotive Gas Turbines

Automotive gas turbines are highly regenerated machines having combustor-inlet temperatures of about 1000 F. This leads to primary-zone temperatures approaching 4000 F, with complete combustion and low emission levels for CO, HC, odor, and smoke.(4) NO_x emission levels are extremely low compared with those of gasoline and diesel engines, but they exceed the proposed 1976 emission standards by a factor of about five.

Table VI-3 shows emissions from four different gas turbines, and compares them with Federal 1976 standards for automobile emissions.(12,16) The General Motors data for 200 hp and 130 hp engines were computed from test data for the 280 hp engine.

Table VI-3. Emissions From Automotive Gas Turbines, g/mi, 7-Mode Driving Cycle

Pollutant	GMT-309(16) 280 hp*	GMT-309(16) 200 hp**	GMT-309(16) 130 hp**	Chrys.*(12) 130 hp	Fed. Std. 1976 (New driving cycle)
CO	7.0	4.7	2.3	3.5	4.7
HC	0.35	0.25	0.13	0.32	0.46
NO	2.3	2.0	1.8	1.9	(0.40)***

*Test data.

**Computer simulation based on larger engine.

***Not established yet but expected to be 0.4 to 0.5 g per mi.

PROSPECTS FOR EMISSION REDUCTION FROM GAS TURBINES BY COMBUSTION MODIFICATION

When current aircraft and industrial gas turbines were developed, the principal criteria for combustor evaluation were size, weight, durability, and performance. Emission of smoke or odors was not considered significant unless it represented a performance loss. Now, however, with the current emphasis on reduction of air pollution, much consideration is being given to pollutants emitted from gas turbines and the means by which they can be reduced. As a first step, visible smoke has been eliminated by development of new combustors. It appears fairly certain that other pollutants will also be reduced significantly in the next decade. The factors involved in such reductions, and some of the means by which reductions might be accomplished, are discussed below. These are, in general, equally applicable to aircraft, industrial, and automotive gas turbines, although each turbine cycle has somewhat different conditions of combustor temperature and pressure.

Typical Gas-Turbine Combustor Design

Figure VI-3 shows a cross section of a modern annular combustor for a large aircraft gas turbine.(8) Although gas turbine combustors vary in size and shape, all incorporate the important features shown in this figure. Air from the compressor outlet, at the left, is slowed in the diffuser; air near the axis enters the shroud and is directed to the primary zone. The remaining air passes between the shell and the combustor liner and is admitted through the liner through various holes and slots. Fuel is admitted through a ring of 64 fuel nozzles, of which one is shown. A substantial part of the primary combustion air enters the primary zone through swirl vanes around the fuel nozzle; the rest enters through rings of holes in the liner. The arrangement of swirl vanes and holes is carefully developed to provide nearly uniform fuel-and-air mixtures throughout the primary zone. Combustion is carried to about 80 percent completion or more in the primary zone, following which the mixture enters the dilution zone, where more air is admitted in high-velocity jets, and combustion is completed rapidly. In some combustors, a distinct secondary-combustion zone is used for completion of combustion before admission of the bulk of dilution air.

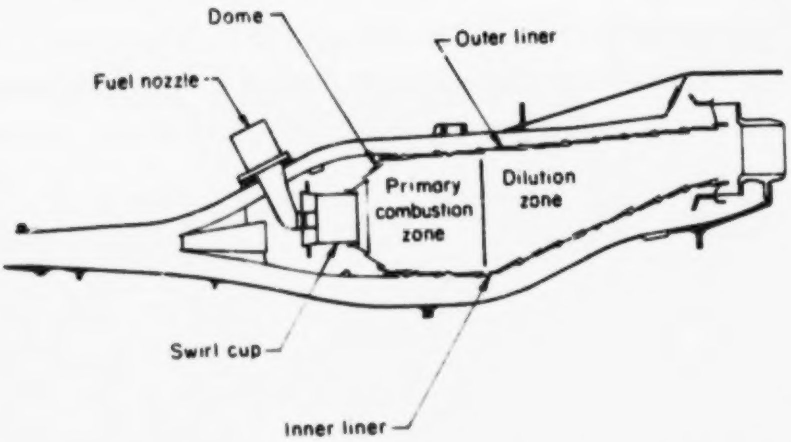


Figure VI-3. Schematic Section of General Electric Annular Combustor for Low Smoke Emission(8)

The combustor liner is constructed of thin sheet metal. It is cooled by a film of air over the inside surface and by external convection and radiation.

Combustor heat-release rates for aircraft combustors at full power are usually about 5,000,000 Btu per ft^3-hr-atm. The combustor of Figure VI-3 operates at a pressure of 25 atm (375 psi) and a heat-release rate of 125,000,000 Btu per ft^3-hr. The corresponding residence time in the primary zone is 2 or 3 milliseconds, with an additional 5 or 6 milliseconds in the dilution zone. The combustor inlet temperature is about 1000 F, and the outlet temperature is about 2300 F. Primary-zone combustion temperatures range from 3600 to 4000 F.

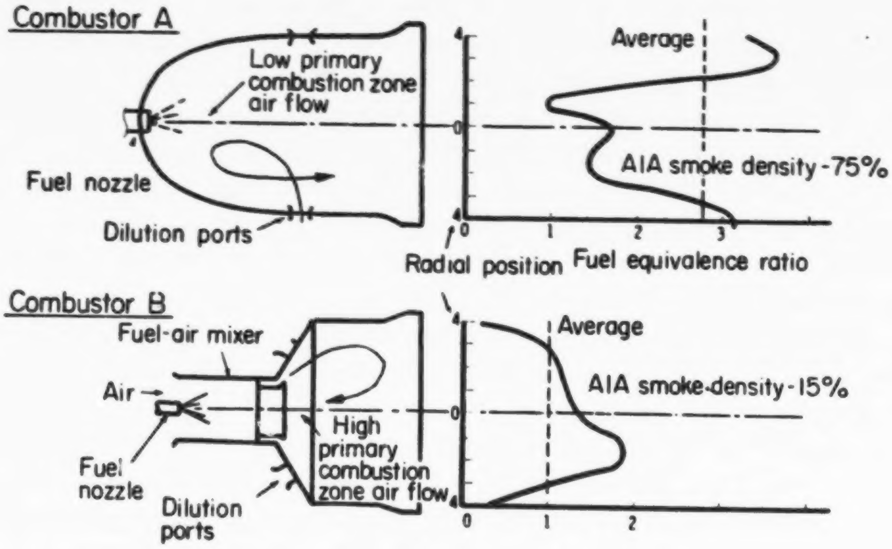
The relation of combustor design to formation of pollutants in combustors of this type is discussed below.

Reduction of Smoke and NO_x

Smoke, or visible concentrations of soot, and NO are formed concurrently in the primary zone during combustion. In general, fuel-rich combustion conditions favor high soot concentrations and low NO concentrations, and fuel-lean combustion conditions favor low soot concentrations and high NO concentrations. The kinetics of smoke formation in rich mixtures have been studied(13), but little is known at the present time about the kinetics of NO formation in rich mixtures. In practice, with perfect mixing, mixtures with fuel-equivalence ratios* up to about 2.0 can burn without formation of visible smoke, but soot forms rapidly in richer mixtures. It is known that the concentration of NO in homogeneous mixtures drops sharply at fuel equivalence ratios above 1.2 or so, but this is hard to confirm in practical combustion chambers because of incomplete mixing and stratification. When both visible smoke and high NO concentrations are emitted by gas turbine combustors, it appears probable that the high NO levels are generated in local lean zones and the high soot levels are generated in local rich zones. It appears possible that, with perfect mixing and with an equivalence ratio somewhat greater than 1.2, combustion should take place without visible smoke and with relatively low NO_x emission.

During the past 5 years, considerable effort has been expended in reducing visible smoke from aircraft gas turbines, and combustors that operate without visible smoke are now available for most engines used in airline and military service.(7,8,9) The means of smoke reduction has been rather extensive redevelopment of the combustor primary zone. Past practice was to operate with full-power equivalence ratios of up to 3.0 in the primary zone, followed by gradual dilution in the secondary zone, where combustion was completed. The new design practice is to limit overall primary-zone equivalence ratio to about 1.5, with a peak value below 2.0. This is achieved by improved air admission through swirl vanes in the dome, injection of air through the fuel-nozzle retaining nuts, and use of small air nozzles to direct jets of air directly into the small rich regions downstream of the fuel nozzles. These changes have eliminated visible smoke, but actual soot concentration in the exhaust is still about half that previously measured with heavy black smoke. With the reduction in visible smoke, the concentration of NO_x in the exhaust has increased significantly.

Figure VI-4 shows two laboratory combustors, one that produces heavy black smoke and one that produces no visible smoke(8). The variation of fuel equivalence ratio across a diameter of the primary zone is shown for both combustors, with an average for each. Combustor A, of



Combustor A
Low primary combustion zone air flow
Fuel nozzle
Dilution ports
Average
AIA smoke density -75%
4
0
4
0
1
2
3
Radial position
Fuel equivalence ratio
Combustor B
Fuel-air mixer
Air
Fuel nozzle
Dilution ports
High primary combustion zone air flow
Average
AIA smoke-density -15%
4
0
4
0
1
2

Figure VI-4. Combined Effects of Primary Combustion Zone Air Quantity and Mixing Effectiveness on Smoke Emission(8)

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*Equivalence ratio as used here is defined as: (fuel-air ratio)/(stoichiometric fuel-air ratio).

conventional design, has an average equivalence ratio of 2.8 (very rich), and fuel is concentrated near the wall. Combustor B has an average equivalence ratio of 1.0, with a peak value of 1.9. Combustor A emits heavy black smoke at simulated full load conditions, and Combustor B emits no visible smoke. The concentration of rich fuel-and-air mixture near the outside of Combustor A makes it easy to light at high altitude, and the large concentration gradient results in stable operation over a very wide range of fuel-air ratios. Combustor B is much more difficult to light and has much narrower stability limits, but does meet engine requirements.

At the present time, design criteria and developed combustors are available for replacement of smoking combustors for almost all air transports, and almost complete refitting of the airline fleet is planned by the end of 1972.(15) Smokeless combustors have also been developed for large industrial gas turbines. However, attention has not, until now, been given to reduction of NO_x emissions from gas turbines.

The reduction of NO_x emissions from gas turbines appears difficult at this time because little success has been achieved and little is known, in quantitative terms, about the design conditions that will best resolve the NO_x and smoke emissions problem. In general, the new "smokeless" combustors generate more NO_x than those they replace. Furthermore, the development trend for new gas turbine engines is toward higher pressure ratios (up to 40:1 in advanced development engines), which lead to higher combustor temperatures and higher NO_x emissions. Thus, considerable progress toward the reduction of NO_x will be required to avoid increasing emissions in coming years.

In considering the theoretical means of reducing NO formation in combustor primary zones, only two approaches appear practical. One is the use of much leaner primary zones to reduce flame temperature; the other is the use of rich primary zones with operation at fuel equivalence ratios above 1.2, to reduce availability of oxygen for NO formation, followed by secondary combustion in an intermediate combustion region with rapid combustion and dilution. Soot formed in the rich primary zone would burn out in the secondary zone if the concentration were not excessive(14). However, neither of these approaches can be carried very far unless consideration is given to the fact that the fuel-air ratio in the primary zone varies by 3 to 1 or more over the engine load range, and the new primary-zone conditions must be compatible with this situation. As an extreme measure, it may be necessary to provide a variable-area stator ring to control air admission to the primary zone, with controls such that primary-zone fuel-air ratio can be held nearly constant over the engine operating range. This would be an expensive change and, probably, would not be acceptable at present low levels of gas turbine pollutant emissions. However, it may prove more acceptable for a high-production application such as automobiles.

General Motors has carried out extensive research on the combustor for the GT-309 automotive gas turbine in attempting to meet proposed 1976 emission standards for NO_x. In carrying out a large number of changes in fuel-air ratio, residence time, and fuel spray distribution they succeeded in reducing NO_x emissions by only 40 percent, and this was accompanied by a significant increase in CO emissions.(15) Their lowest NO_x emissions were obtained using a very lean primary zone, in combination with early quenching of the flame with dilution air. Full-load NO_x emissions were reduced from about 125 ppm to about 75 ppm by these changes.

The prospects for reducing flame temperature by recirculation of exhaust gas appear poor. Cooled combustion products are not available at combustor pressure, and turbine exit gas at high temperature cannot easily be cooled for introduction into the compressor inlet.

Reduction of CO, HC, and Odor

CO, HC, and odor are products of incomplete combustion emitted from aircraft gas turbines at the low power settings used for idle and taxi operation; emission of these pollutants is minor at cruise and take-off power levels. At low power settings, fuel flow rates are very low and fuel atomization is marginal, which leads to deterioration of combustion. Furthermore, the primary zone is very fuel lean, with excess air of 200 to 500 percent. This results in the quenching of partially burned combustion products by dilution with excess air. Finally, temperatures and pressures are low. As shown in Figure VI-2, the combustion efficiency at idle for various engines ranges from 85 to 96 percent, indicating that from 4 to 15 percent of the fuel fired is emitted as products of incomplete combustion.

With combustors in present engines, combustion efficiency is near 100 percent over the important upper part of the operating range where nearly all of the fuel is burned. Any changes to improve combustion at idle must be such that efficiency at higher loads is not compromised.

The means by which combustion efficiency might be improved at idle are not obvious, and no research toward such improvement has been carried out. However, it appears desirable to change the mode of combustor operation in some way to improve the conditions described above. Several ways by which this could be done are:

1. Use variable geometry to reduce air flow into the primary zone at reduced power settings, maintaining nearly stoichiometric fuel-air ratios over the load range.

2. Change the fuel system to permit fuel admission through a limited number of fuel nozzles at idle, so that each fuel nozzle would admit sufficient fuel for good atomization, and the combustion region at each fuel nozzle would be large enough for good combustion efficiency. The fuel system could operate on alternate fuel nozzles at low loads, for example, and all fuel nozzles would open at a higher power setting. A change of this type is most suitable for annular combustors; it would require alteration of the fuel control and fuel manifolds.

3. Utilize air atomization at low loads to improve fuel atomization.

It would be difficult to justify the cost and complexity of a variable-geometry primary-zone air control for aircraft gas turbines, but fuel-system modifications, if effective, could probably be justified. Industrial gas turbines, in general, operate very little at idle and low power settings, and emissions at these conditions are not significant. Finally, automotive gas turbines, being highly regenerated and utilizing air atomization of fuel, have achieved acceptable levels of CO, HC, and odor emissions. Although they use only one fuel nozzle, the concept of variable-air-admission geometry could be used to improve both idle emissions of CO and HC and high-power-level emissions of NO_x.

EXTERNAL-COMBUSTION ENGINES

Two types of external combustion engines are of interest for possible future application to passenger automobiles: the Rankine-cycle engine and the Stirling-cycle engine. The Rankine cycle is a vapor cycle with an organic liquid or water as the working fluid. The Stirling cycle is a gas cycle with compressed gas as the working fluid. Both have the potential characteristic of very low pollutant emissions.

The incentive for development of external-combustion engines and the automotive gas turbine is the potential low emission of air pollutants by such engines. At the present time the automobile is the source of about 60 percent by weight of all pollutant emissions, so that any change that significantly reduces the emissions from automobiles will have a major impact on air pollution.

Table VI-4 summarizes the incentives for continuous-combustion automotive engine R&D. The emission levels that appear probable for an improved automotive gas turbine represent a reduction of 90 percent below emissions of 1970 vehicles. The possible emission levels from an ultimate external-combustion engine may represent a 95 to 98 percent reduction.

Table VI-5 summarizes the present status of emissions from continuous-combustion automotive engines, and compares them with emissions for 1970 vehicles and 1976 standards for automotive engines. Those emissions that exceed the 1976 standards are underlined for easy identification. The table shows that NO_x levels are generally higher than the 1976 standards, although HC and CO emission standards are met by most engines.

Table VI-4. Incentives for Development of Continuous-Combustion Automotive Engines

Pollutant	1970 Vehicle, 1972 Procedure	Federal 1976 Standard	Improved Gas Turbine*	Ultimate External Combustion Engine*
HC, g/mi	4.6	0.46	0.22	0.1
% reduction	–	*90*	*91*	*95*
CO, g/mi	47	4.7	2.4	0.4
% reduction	–	*90*	*90*	*98*
NO_x, g/m	*6.0***	(0.4)***	1.0	0.3
% reduction	–	*93*	*83*	*95*

*Battelle estimate.
**Representative value; no Federal standards are applicable.
***Not established yet but expected to be 0.4 to 0.5 g per mi.

Table VI-5. Emissions from Present Conventional and Unconventional Automotive Engines

	ppm			g/mi		
	HC	CO	NO$_x$	HC	CO	NO$_x$
Uncontrolled IC engine	900	3.5%	1500	11.5	80	5–6
1970 IC engine, 1972 procedure				4.6	47	6–7*
FEDERAL 1976 IC ENGINE STANDARDS				0.46	4.7	(0.40)**
Automotive Gas Turbines						
General Motor GT-309 Technology(16)						
280 hp test data – standard burner	–	–	–	0.29	2.5	3.75
lean burner	–	–	–	0.34	7.4	2.25
130 hp simulation – standard burner	–	–	–	0.12	1.0	2.80
lean burner	–	–	–	0.15	2.9	1.75
Chrysler field-trial model A-831(12)	–	–	–	0.32	23.5	1.9
Automotive Rankine-Cycle Engines						
General Motors SE-101 vehicle(17)	–	–	–	1.0	8.0	2.2
General Motors SE-124 vehicle(17)	–	–	–	0.3	1.0	1.7
Marquardt laboratory combustor(18)	10	120	120	–	–	–
TECO auto design study(19)	15	60	40	0.05	0.35	0.25
1923 Doble(17)	–	–	–	1.4	3.9	2.0
Automotive Stirling-Cycle Engines						
Philips 80-hp Stirling-cycle engine(20)						
Without exhaust gas recirculation	–	79	107	–	–	–
With 33 percent exhaust gas recirculation	–	122	40	–	–	–
General Motors Stir-Lec I Hybrid Car(20)	1–2	100–200	550–1100	0.1	1.0	2.6
General Motors 10-hp Stirling engine(20)						
Full load: Air-fuel ratio 25	2.0	30	500	–	–	–
Air-fuel ratio 20	1.0	40	1050	–	–	–
Half load: Air-fuel ratio 40	0.6	40	130	–	–	–
Air-fuel ratio 20	2.0	130	750	–	–	–

*Battelle estimate.

**Not established yet, but expected to be about 0.4 to 0.5 g per mi.

RANKINE-CYCLE ENGINES

The Rankine-cycle engine is considered to have great promise as a potential replacement for the automotive gasoline engine because it can burn fuel continuously at atmospheric pressure under carefully controlled conditions. It is reasoned that these combustion conditions are conducive to the lowest practical level of emissions of NO_X, CO, and HC.

However, development of Rankine-cycle engines suitable for future automotive application has just begun, and the desired low emission levels have not been demonstrated over the range of conditions encountered in an automotive application. Accordingly, APCO is proceeding with an extensive R&D program to develop the technology needed for advanced Rankine-cycle engines and, eventually, to develop complete automotive propulsion systems. The combustion system for the Rankine-cycle engine must meet particularly demanding requirements.

Combustion-System Requirements

The important design criteria that must be met by a Rankine-cycle combustion system include the following:

- Wide turn-down range
- Compact design
- Low noise level
- Moderate pressure drop
- Very low emissions of NO_X, CO, HC, smoke, and odor
- Simple and practical control systems
- Suitability for widely available fuels.

Wide turn-down range is a particularly important aspect of any automotive engine. It is estimated that the idle fuel-consumption rate for an automotive Rankine-cycle engine will be only 1 to 3 lb fuel per hr, and the full-load rate will be about 100 lb per hr, for a turn-down ratio of 30:1 to 100:1. At the present time, no known burner will operate over a 100:1 turn-down ratio, and it is expected that development of a low-emission burner for such a turn-down range will require a considerable extension of technology. Although many continuous-combustion systems operate with very low emission levels at one firing rate, the development of a wide-range burner having low emission levels at all firing rates will be a difficult task.

Alternatively, an on-off burner control system might be used, or a burner might be modulated through a part of the operating range, with on-off control for the lowest power levels. The important criteria for on-off control are the frequency of cycling, which depends upon boiler heat-storage capacity, and the effects of on-off transients upon emissions. It is now popular to propose boilers of minimum size, weight, and cost, having virtually no internal water storage. These boilers have low heat-storage capacity and are, thus, suitable only for use with a highly responsive modulating burner and controls. The addition of boiler water-storage capacity can increase the heat storage and lengthen the cycling periods for on-off burner operation at the expense of added size and weight, and of slower start-up.

Compact design is required to minimize overall engine size. A heat-release rate of 1,500,000 Btu per ft^3-hr, requiring a volume of 1.3 ft^3, has been specified by APCO as being desirable for automotive power plants. This heat-release rate appears reasonable with moderate pressure drop.

Pressure drop for the Rankine-cycle burner must be moderate, at about 12 in. wg or less, to limit fan power consumption to a reasonable value of about 1.5 hp. With this pressure level at full load and a minimum pressure drop of about 0.5 in. wg, a turn-down ratio of 5 can be obtained with a conventional burner. Additional turn-down would require either variable geometry, variable fuel-air ratio, on-off operation, or other unconventional features.

Noise level is highly dependent upon burner pressure drop and should be acceptable with the above limit on pressure drop.

The emission levels of NO_x, CO, HC, smoke, and odor will depend greatly upon details of design and operation. It appears necessary that: (1) a hot, intense flame be developed at all firing rates from 1 lb per hr to 100 lb per hr, (2) that fuel-air ratio be controlled closely, and (3) that excessive flame temperature at high firing rates be avoided – either by use of boiler cooling surface to limit flame temperature, by control of fuel-air ratio for lean operation, or by two-stage combustion. Exhaust-gas recirculation is another technique that can be used to reduce NO_x emission. Fuel atomization and distribution within the combustion space have a significant influence upon emission levels.

A practical detail of great importance is the means of control of fuel and air flow rates. It will be necessary for a control system to regulate the fuel flow and the air flow to the burner in exactly the right quantities to meet driver demands.

Finally, the fuel to be burned must be one that can be made available in great quantities to the motoring public. Fortunately, a continuous-combustion system does not require high-octane fuels, and simple wide-boiling-range distillate mixtures can be burned.

Emission Levels of Reported Rankine-Cycle Combustion Systems

Emission levels for four Rankine-cycle combustion systems are known to have been published. Three Rankine-cycle automobiles have been operated over the 7-mode cycle by General Motors(17), and an experimental low-emission combustion system has been tested by Marquardt under a NAPCA contract(18). Emission levels for these combustion systems are included in Table VI-5.

The two General Motors vehicles were considerably different in design and operation. The SE-101 engine, built by the GM Research Laboratory and tested in a 5500-lb vehicle, utilized very high combustion intensity, at 3.75 x 10^6 Btu per ft^3-hr. It employed a fixed-geometry burner and a modulating control system. The combustion control was based upon driving the fuel pump, combustion-air fan, and feedwater pump by the expander through a two-speed drive. The low drive speed was about adequate for steady-state operation, and high drive speed provided for acceleration. A two-step fuel-nozzle bypass control regulated the outlet steam temperature. The air-fuel ratio at the burner was 25:1 at high fuel flow and 35:1 at low fuel flow. On-off control was used as needed. The pollutant emissions from this burner, shown in Table VI-5, were considerably higher than the 1976 standards.

The General Motors SE-124 vehicle incorporated a boiler built by Besler Developments, for which the combustor heat-release rate was 0.95 x 10^6 Btu per ft^3-hr. As used in a 3500-lb vehicle, emission levels were lower than for the SE-101, as shown in Table VI-5. However, NO_x emissions exceeded the 1976 standards by a factor of 4.

The Marquardt combustion system was operated only at high firing rates with no attempt to obtain the turn-down range required by an operating engine. Under the test conditions the emission levels were extremely low. Thermo Electron Corporation (TECO) has used the Marquardt results in a design study of a Rankine-cycle passenger car(19) and results are shown in Table VI-5. Emission levels calculated for all pollutants were far below the 1976 standards. However, these results make no allowance for on-off operation or for a wide turn-down range, either of which would increase emission levels.

The excellent low-emission performance of the Marquardt experimental burner demonstrates that extremely low emission levels are possible under ideal conditions. It appears probable that, with sufficient R&D, a fully modulated combustion system meeting Federal 1976 emission standards can be developed.

STIRLING-CYCLE ENGINES

In the Stirling-cycle engine, a gaseous working fluid is heated in a heat exchanger fired by an external combustor. The exhaust from this heat exchanger is very hot at about 1400 F, and a regenerator is used to recover part of the exhaust heat and improve thermal efficiency. In this regenerator, the combustion air is heated to 1000 F or more.

The combustion-system requirements for the Stirling-cycle engine are similar to those for the Rankine-cycle engine as discussed above. However, the use of highly preheated combustion air increases adiabatic flame temperature and the potential for NO_x emissions.

Stirling-cycle engines have been under development for more than 30 years by the N. V. Philips Research Laboratories of The Netherlands, and more recently, by General Motors under license to Philips. A recent paper(21) discusses emission levels from a 10-hp General Motors engine and an 80-hp automotive engine developed by Philips. Results, including interpretation in terms of automotive application, are summarized at the bottom of Table VI-5. The Philips unit emitted 79 ppm of CO and 107 ppm of NO_x with normal firing. When exhaust-gas recirculation, at 33 percent, was introduced, emission concentrations changed to 122 ppm CO and 40 ppm NO_x.

The General Motors Stir-Lec I was a hybrid car utilizing the 10-hp GM Stirling engine in combination with a battery and electric drive system. The Stirling engine drove an alternator to charge the battery and power the electric drive motor. Emission characteristics of the car are shown in Table VI-5.(20) The emission levels for HC and CO were below Federal 1976 standards, but NO_x was high by a factor of 6.

The 10-hp General Motors unit was shown to be sensitive to fuel-air ratio and to air preheat temperature. As shown in Table VI-5, HC concentration was very low, at 0.6 to 2 ppm; CO concentration varied from 30 to 130 ppm under different conditions, and NO_x was high, at 130 to 1050 ppm.

It appears probable that an automotive Stirling-cycle engine could meet the Federal 1976 emission standards, based upon the low emission of NO_x shown for the Philips engine with exhaust-gas recirculation, although the General Motors results without this feature show excessive NO_x emissions.

SUMMARY OF CURRENT AND RELEVANT COMBUSTION R&D

Table VI-6 summarizes current combustion R&D for continuous-combustion engines. All of the projects listed are related to either gas turbines or Rankine-cycle engines.

Most of the gas-turbine research is related to reduction of emission of smoke or of NO_x and to development of techniques and instrumentation for emission measurements; this work is supported or planned by APCO, FAA, and the USAF Aero Propulsion Laboratory. As a continuing effort, emission data are to be taken for all future combustor tests at the NASA Lewis Research Center, and it is expected that this will eventually provide sufficient data to permit parametric analyses of design variables in terms of pollutant emissions.

The R&D related to low-emission combustion systems for Rankine-cycle engines are those projects supported by NAPCA.

R&D NEEDED TO FILL GAPS IN TECHNOLOGY

The R&D needed to fill technological gaps related to continuous-combustion engines is of two types:

- Long-range fundamental research that will provide guidance regarding physics and kinetics of combustion, and the factors influencing formation and decomposition of various pollutants. (Such studies are discussed in Chapter VIII.)
- Short-range applied research to develop low-emission combustion systems to meet immediate needs.

It appears that fundamental research will require many years, and that results will not assist greatly in immediate short-range applied research. However, it is to be expected that the fundamental information and understanding of combustion pollutant formation developed will eventually guide future applied research.

Table VI-6. Current Combustion R&D – Continuous-Combustion Engines

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VI-a	Study of continuous flow combustion systems for external combustion vehicle power plants	NAPCA-DMVR&D CPA 22-69-128	Marquardt Co. Van Nuys, Calif.	C. V. Burkland	Develop low-emission burner for external-combustion vehicle power plants	96,683 (FY '69)
VI-b	Development of low-emission burner for rankine cycle automobile engine	NAPCA-DMVR&D EHS 70-106	Solar Div. Internat. Harvester San Diego, Calif.	W. Compton	Develop low-emission burner for Rankine cycle engines	151,254 (FY '70)
VI-c	Development of low-emission burner for rankine cycle automobile engine	NAPCA-DMVR&D EHS 70-117	Battelle Mem. Inst. Columbus Lab. Columbus, Ohio	H. R. Hazard	Develop low-emission burner to Rankine cycle engines	93,300 (FY '70)
VI-d	Evaluation of low-emission burner for rankine cycle automobile engine	NAPCA-DMVR&D EHS 70-125	Paxve, Inc. Newport Beach, Calif.	Mr. Zwick	Develop low-emission burner to Rankine cycle engines	73,000 (FY '70)
VI-e	Develop sampling system and measure exhaust emissions from contractor's gas turbine engines	NAPCA CPA 22-69-84	Williams Res. Corp. Walled Lake, Mich.	H. B. Moore	–	45,000 (FY '69)
VI-f	Design criteria for reduction of NO_x emissions from aircraft turbojet engines	NAPCA-DMVR&D & FAA	Northern Res. & Engr. Corp. Cambridge, Mass.	R. Fletcher C. hastress	Develop design parameters for control of NO_x emission from high-pressure-ratio gas turbine-combustors	97,800 (FY '70)
VI-g	Study of emissions from high inlet temperature gas turbines	NAPCA E-HSD 71-Neg. 50	Not selected	–	–	–
Vi-h	Low NO_x emission combustor for automobile gas turbine-engines	NAPCA E-HSD 71-Neg. 104	Not selected	–	Develop design data and criteria for automotive gas turbine combustors to meet 1980 emission goals	
VI-i	Design criteria for reduction of CO and UHC emissions from aircraft turbojet engines	FAA	–	–	–	–
VI-j	Study of the visibility of exhaust smoke from aircraft engines	NAPCA-DMVR&D & FAA	IIT Res. Inst. Chicago, Illinois	M. Jackson J. Stockham	–	91,000 (FY '69)
VI-k	Parametric study of combustor design variables and their relation to pollutant emissions from aircraft gas turbines	NASA	NASA Lewis Res. Ctr. Cleveland, Ohio	H. Childs	–	15,000 (FY '70)
VI-l	Reduction of CO and UHC emissions from aircraft turbojet engines	U.S. Air Force Aero Propulsion Lab.	–	–	Study mechanisms and develop new designs to reduce CO and UHC emissions at low power	–
VI-m	Fuel additives to reduce NO_x emissions from aircraft turbine engines	U.S. Air Force Aero Propulsion Lab.	–	–	–	– (FY '71)

Table VI-6. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VI-n	Turbine engine exhaust emission measurement	U.S. Air Force Aero Propulsion Lab.	–	–	Develop procedures and equipment, construct mobile measurement system	–
VI-o	Turbo propulsion augmenter exhaust emissions	U.S. Air Force Aero Propulsion Lab.	–	–	Develop 3500 F sampling system and measure emissions from afterburner	– (FY '71)
VI-p	J79 engine low-smoke combustor development	U.S. Air Force Aero Propulsion Lab.	General Electric Co. Flight Propulsion Div. Cincinnati, Ohio	D. W. Bahr	–	1,000,000*
VI-q	Development of instruments and procedures for measuring gaseous pollutants from aircraft turbine engines	Soc. Auto. Engr.	Soc. Auto. Engr. Committee E-31	Phillip Sallee, Ch. American Airlines	–	–
VI-r	Development of low-smoke combustors for JT8D, JT3 and J54 engines	–	Pratt & Whitney Aircraft East Hartford, Conn.	J. J. Faitani	–	6,000,000*
VI-s	Research into the reduction of noise and smoke from gas turbine engines	–	National Gas Turbine Establishment Pyestock, Farnborough Hampshire, England	–	–	–
VI-5	Studies of the reduction of smoke and nitrogen oxides and unburned fuel emissions from jet engines by means of mechanical modifications and fuel additives	–	Rolls-Royce, Ltd. Scientific Development Labs. Derby, England	P. Walker	–	–

*Battelle Estimate.

The immediate short-range problems that require attention include the following:

- Development of gas-turbine combustors that emit less NO_x than current combustors.
- Development of new combustor concepts to greatly reduce the emission of HC, CO, and odor at idle and low-power settings
- Development of low-emission combustors for the special conditions encountered in automotive gas turbines.
- Development of special low-emission combustors for automotive Rankine-cycle engines having the wide turn-down range needed for such application.

R&D OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Five R&D opportunities related to continuous-combustion engines are recommended for the 5-Year Plan. All of these are short-range applied R&D projects to develop low-emissions combustion systems. Three of these are aimed at reduction of emission from aircraft and industrial gas turbines, one is for development of a low-emission combustor for automotive gas turbines, and one is for development of low-emission combustors with wide turn-down range for automotive Rankine-cycle engines. Recommended R&D opportunities are as follows:

Aircraft and Industrial Gas Turbines

VI-1. Primary-zone design to reduce NO_x emission

VI-2. Secondary-combustion and dilution zone design to reduce NO_x

VI-3. Criteria for reduction of CO, HC, and odor at idle and low power

Automotive Gas Turbines

VI-4. Development of a low-emission automotive-size gas-turbine combustor prototype

Automotive Rankine-Cycle Engine

VI-5. Development of low-emission combustors for Rankine-cycle automotive engines.

The R&D opportunities designated VI-1, VI-3, and VI-5 have been identified by APCO as future areas of research and some projects along these lines are being initiated. It will be noted from Table VI-6 that both FAA and USAF Aero Propulsion Laboratory are planning research to reduce emissions from aircraft gas turbines, and coordination of these efforts with APCO efforts is recommended.

R&D Opportunity: VI-1

Related to: V-4; VI-2; VIII-1, 25, 26; VI-f, k, h, t

Analytical and Experimental Research on Relation of Gas-Turbine Combustor Primary-Zone Design to Emission of NO_x

Technical Objective and Approach

The objective is the reduction of NO_x emission from aircraft and stationary gas turbines.

The approach should consist of analytical modeling of the primary zone to study kinetics and physics of the flame, followed by experimental confirmation of the model and determination of experimental coefficients. The principles and general design guidelines developed should be investigated using an existing engine. However, this experimental combustor need not meet all usual operational requirements, but simply provide realistic primary-zone mixing, turbulence, pressure, and temperature conditions. Specific design criteria should be formulated on the basis of analytical and experimental results.

Rationale and Incentive

Some turbojet engines emit rather low levels of NO_x while others emit very high levels. It is believed that the NO_x level is dependent upon the primary-zone equivalence ratio and upon the completeness of mixing, but the optimum equivalence ratio for different operating pressures and inlet-air temperatures is not known. It is anticipated that mathematical modeling of primary-zone physical conditions and kinetics will permit study of these factors and guidance toward development of future combustors.

Work in this area is already in progress under an FAA contract with joint APCO funding.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$400

R&D Time Range: 2-3 years

Recommended 5-year Funding, 1000's: $400

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	200	–	–	–	–

Evaluation

Sources Affected: Stationary and Aircraft Gas Turbines

Relative Potential Benefit (overall rating): Medium Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						30-50				–
Expected						47				–
Fraction of ECC Emissions Affected						0.034				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						1.60				1.60

Implementation Time, years: 3-5 most likely: 4

Relative Implementation Cost: Very Low

Relative Priority Rating: C

An explanation of the evaluation factors used in the priority ranking is contained in Chapter II and Appendix A.

R&D Opportunity: VI-2 Related to: VI-1; VIII-1, 25, 27; VI-f, k, h, t

Analytical and Experimental Research to Explore Relation of Gas-Turbine Secondary-Combustion- and Dilution-Zone Design to NO_x Emission

Technical Objective and Approach

The objective is to explore the relation of secondary-combustion and dilution-zone design to emission of NO_x.

The approach should include using an analytical model relating local temperatures, oxygen concentrations, and mixing conditions to residence time for various geometric assumptions together with suitable kinetic equations for study of the formation and decomposition of NO_x. This should be followed by an experimental study to confirm results of the analytical study and to develop design criteria and experimental coefficients for future application in the analytical design of combustors.

Rationale and Incentive

In the gas turbine combustor, combustion can be carried out with a deficiency of air in the primary zone and addition of secondary air to complete the combustion in a secondary zone, with subsequent addition of dilution air to reduce gas temperature to the range of 1500 to 2500 F. It is believed that the emission of NO_x, CO, and smoke can be influenced by the dilution ratios, residence time, and mixing characteristics of the secondary and dilution zones, in which combined residence time is less than 10 milliseconds. Optimum design should minimize emission of NO_x, CO, and smoke.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$500
R&D Time Range: 2-3 years

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	200	200	–	–	–

Evaluation

Sources Affected: Stationary and Aircraft Gas Turbines
Relative Potential Benefit (overall rating): Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range						0-30				–
Expected						15				–
Fraction of ECC Emissions Affected						0.034				–
Noncombustion Controls Factor						0				–
Relative Potential Benefit Factor						0.51				0.51

Implementation Time, years: 3-5 most likely: 4 Relative Implementation Cost: Very Low

Relative Priority Rating: D

R&D Opportunity: VI-3 Related to: VI-4; VIII-4, 6, 9, 17, 25, 26; VI-i, k, l

Analytical and Experimental Research to Develop Criteria for Reduction of CO, HC, and Odor Emissions From Aircraft Gas Turbines at Idle and Low Power

Technical Objective and Approach

The objective is to devise means of improving combustion efficiency and reducing emission of unburned hydrocarbons at idle and low power without compromising performance at higher power levels.

The approach should include analytical consideration of physical changes to alter distribution of fuel in the primary zone at low loads to provide greater concentration of combustion in locally rich zones (including one or more fuel nozzles) or by utilizing variable-geometry concepts to reduce air flow into the primary zone at low loads and thus avoid excessively lean combustion conditions. Satisfactory concepts must be suitable for practical application to aircraft combustors, considering weight, simplicity, and reliability. An experimental program is also recommended.

Rationale and Incentive

The design of the primary zone for an aircraft gas turbine is such that fuel-air ratios vary over a range of about 5:1 between idle and full-load operation. This results in very lean combustion conditions at low loads, with relatively poor combustion efficiency and high emission levels of partly burned fuel. The low efficiency is believed to result from quenching of the flame with cold air before combustion is completed, due to the lean conditions. This problem is most important with aircraft gas turbines, which are of large size and spend considerable ground time at idle and taxi conditions. This creates odor problems in aircraft areas. A successful program should result in elimination of most of the exhaust odors, unburned hydrocarbons, and CO associated with airport operations. Demonstration of successful combustion modifications under laboratory conditions should lead to their application in future engines and, possibly, development of retrofit fuel system modifications for current engines.

Work in this area is planned for FY '71 by the FAA and by the USAF Aero Propulsion Laboratory.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $450-$650 Recommended 5-year Funding, 1000's: $650

R&D Time Range: 2-3 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	250	200	200	–	–	–

Evaluation

Sources Affected: 90 Percent of Aircraft Gas Turbine Emissions of CO, HC, and Odor

Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range		50-80	50-80		50-80					–
Expected		68	68		68					–
Fraction of ECC Emissions Affected		.0086	.019		.076					–
Noncombustion Controls Factor		0	0		0					–
Relative Potential Benefit Factor		0.58	1.29		5.17					7.04

Implementation Time, years: 3-5 most likely: 5 Relative Implementation Cost: Low

Relative Priority Rating: B

R&D Opportunity: VI-4

Related to: VI-1, 2, 3,; VIII-25, 26; VI-f, h, i, k, l, t

Development of a Low-Emission Automotive-Size Gas-Turbine Combustor Prototype

Technical Objective and Approach

The objective is the development of a prototype combustor for an automotive gas turbine that meets Federal 1976 emission standards.

The approach should include utilizing the best currently available knowledge regarding the influence of combustor design upon emissions to develop a low-emission automotive gas turbine combustor. This may necessitate the introduction of new hardware concepts such as variable geometry.

The combustor must meet all performance and operational requirements of a production model automotive gas turbine and should be installed in a suitable turbine for demonstration purposes. Heavy-duty automotive gas turbines, suitable for buses and trucks, are now near introduction, and production models should be available at the end of the program for experimental investigation of the applicability of these design criteria.

Rationale and Incentive

In the development of past automotive gas-turbine combustors, minimum emissions of NO_X and unburned hydrocarbons have not been primary performance requirements. Nevertheless, emission levels of current gas turbines approach the proposed 1976 emission standards, and it appears probable that considerably lower emission levels can be achieved. The present automotive gas-turbine designs include effective regenerators, leading to very high combustor flame temperature and high (by 1976 standards) NO_X emission levels. Thus, it may be necessary to introduce rather different design concepts to meet NO_X emission standards.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $400-$800

R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $800*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	200	200	200	200	–	–

Evaluation

Sources Affected: Mobile Gasoline Engines

Relative Potential Benefit (overall rating): Very High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_X	Lead	SO_X	Ash	Σ
% Reduction, Range	90-95	85-91	85-91			60-90	100			–
Expected	94	89	89			78	100			–
Fraction of ECC Emissions Affected	.096	.48	.34			.25	.59			–
Noncombustion Controls Factor	.5	.8	.8			.2	.8			–
Relative Potential Benefit Factor	4.51	8.54	6.05			15.60	11.80			46.50

Implementation Time, years: 8-12 most likely: 10

Relative Implementation Cost: High

Relative Priority Rating: A

R&D Opportunity: VI-5 **Related to: VIII-25, 26; VI-a, b, c, d**

Development of Low-Emission Combustors for Rankine-Cycle Automotive Engines

Technical Objective and Approach

The objective is the development of one or more demonstration models of combustion systems suitable for application to automotive Rankine-cycle engines.

The approach should include both analytical and experimental work and should be heavily hardware oriented. It is anticipated that, in the near future, various new concepts for such combustion systems will be suggested. The most promising of these should be evaluated and, if warranted, work should be carried through an exploratory development phase. The technology developed during this program should provide the technical base for future development and application of Rankine-cycle automotive engines.

Rationale and Incentive

The low-emission Rankine-cycle combustor must operate over a turndown range much wider than that of any currently available burner: a turn-down ratio of 100:1 to 30:1, depending upon engine application details. No burner meeting this turndown requirement with low emissions has yet been demonstrated, and this appears to be a key element in the success of any future Rankine-cycle automotive application. This requirement, plus the added requirements of compactness, low noise level, and moderate power demand for the combustion-air fan and fuel pump, add up to a difficult and challenging development opportunity that will require a considerable extension of the current state of art of burner technology. With satisfactory development, it should be possible to meet or exceed the Federal 1976 automotive emission standards.

Work in this area has been started under several APCO contracts.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $600-$1,200 Recommended 5-year Funding, 1000's: $1,200
R&D Time Range: 2-4 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	500	300	200	200	–	–

Evaluation

Sources Affected: Mobile Gasoline Engines
Relative Potential Benefit (overall rating): Very High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	90-95	90-98	90-95			90-95	100			–
Expected	94	94	93			93	100			–
Fraction of ECC Emissions Affected	0.79	.35	.26			.20	.49			–
Noncombustion Controls Factor	.5	.8	.8			.2	.8			–
Relative Potential Benefit Factor	3.71	6.58	4.84			14.88	9.80			39.81

Implementation Time, years: 10-15 most likely: 12½ Relative Implementation Cost: High

Relative Priority Rating: A

R&D Opportunity: VI-New Concepts

Provision for Exploring New Concepts and New R&D Opportunities that Evolve from the Program, Accelerating Promising R&D, or Conducting Demonstrations of Promising Concepts for Reducing Emissions from Gas Turbines and External-Combustion Engines by Combustion Modification

Technical Objective and Approach

The objective is to provide for long-range flexibility in the R&D program to enable APCO to take advantage of opportunities that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the R&D program to explore the feasibility of new and novel concepts and to accelerate research, development, and demonstration of promising concepts for reducing emissions by combustion-process modification. Worthwhile ideas for combustion-process modification to reduce emissions from gas turbines and external-combustion engines might originate as the result of novel design concepts or through in-depth understanding derived from well-planned R&D. The merits of specific R&D opportunities should be decided by evaluating the particular concepts as they evolve.

Rationale and Incentive

Reduction of emission levels from gas turbines and external-combustion engines will be a continuing goal, especially if such engines are applied to passenger automobiles. It is probable that, as presently foreseeable improvements are implemented, other opportunities for combustion modification to reduce emissions will become evident.

Recommended Funding Allocation

	'71	'72	'73	'74	'75	
Funding by Fiscal Year, $1000's	–	100	150	150	200	5-year Funding, 1000's: $600

Evaluation

This R&D Opportunity is unranked. Potential benefit, implementation time, implementation cost, and funding level for each specific opportunity must be evaluated when the opportunity is identified. The suggested funding level anticipates effort on several R&D opportunities.

Relative Priority Rating: N

TABLE VI-7. SUMMARY BY PRIORITIES

CONTINUOUS-COMBUSTION ENGINES – GAS TURBINES AND EXTERNAL-COMBUSTION ENGINES

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
A	VI-4	Development of a Low-Emission **Automotive-Size Gas-Turbine Combustor** Prototype	–	200	200	200	200	–	800	–
A	VI-5	Development of Low-Emission **Combustors for Rankine-Cycle** Automotive Engines	X	500	300	200	200	–	1,200	–
		Totals, Priority A		700	500	400	400		2,000	
B	VI-3	Analytical and Experimental Research to Develop **Criteria for Reduction of CO, HC, and Odor** Emissions From Aircraft Gas Turbines at **Idle** and **Low Power**	–	250	200	200	–	–	650	–
C	VI-1	Analytical and Experimental Research on Relation of **Gas-Turbine Combustor Primary-Zone Design** to Emission of NO_x	X	200	200	–	–	–	400	–
D	VI-2	Analytical and Experimental Research to Explore Relation of **Gas-Turbine Secondary-Combustion- and Dilution-Zone Design** to NO_x Emission	–	100	200	200	–	–	500	–
N	VI-N	Provision for Exploring **New Concepts** and **New R&D Opportunities** that Evolve From the Program, **Accelerating Promising R&D,** or **Conducting Demonstrations** of Promising Concepts for Reducing Emissions From Gas Turbines and External Combustion Engines by Combustion Modification	–	–	100	150	150	200	600	–
		Totals, All Priorities		1,250	1,200	950	550	200	4,150	

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Chapter VII

RECIPROCATING INTERNAL-COMBUSTION ENGINES

Frederick A. Creswick

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CHAPTER VII

RECIPROCATING INTERNAL-COMBUSTION ENGINES

SCOPE OF CHAPTER AND BACKGROUND

This chapter deals with possibilities for emission reduction by modification of combustion in reciprocating, or piston-type, internal-combustion (IC) engines for both vehicular and stationary applications. Certain types of rotary IC engines are also included because their combustion processes are essentially the same.

IC engines are important sources of air pollutants. This is particularly true of the automotive gasoline engine, both because of the large number of such engines and because they are, compared with many other combustion sources, heavy emitters of many of the pollutants of current concern. Table VII-1 shows the percentage contribution of gasoline, diesel, and gas engines to the nationwide total emission of pollutants from all energy-conversion combustion (ECC) sources.

Table VII-1. Emissions From Reciprocating IC Engines*

	Contribution to Nationwide ECC Emissions, percent		
Pollutant	Gasoline Engines	Diesel and Gas Engines	Total
Products of Incomplete Combustion			
Combustile Particulate	12	18	30
CO	97	1	98
Gaseous HC	93	5	98
PNA	6	nil	6
NO_x	39	19	58
Combustion-Improving Additives			
Lead	99	nil	99
Fuel Contaminants			
SO_x	1	<1	1
Ash (Noncombustible Particulate)	nil	nil	<1

*Derived from data in Table II-1.

ENGINE TYPES

Two basic types of IC engines must be considered: spark-ignited gasoline engines and diesel or compression-ignition engines. Although it is assumed that readers are acquainted with the basic operation of both engine types, attention is called to some of the more important characteristics of each.

Gasoline Engines

Three descriptors are often used synonymously to refer to the same type of engine: gasoline, spark ignited (SI), and Otto cycle. These engines generally use gasoline as fuel, the fuel-air charge is generally homogeneous, and combustion is spark ignited. There are various types of these engines that differ in construction, application, and exhaust-emission characteristics; six types are described below.

The 4-stroke-cycle, multicylinder engine is the most widely used type of gasoline engine and is available in automotive, industrial, and aircraft versions. Automotive engines are designed for use in motor vehicles; therefore, light weight, compactness; responsiveness, and capability of operation over a wide range of speeds and loads are required. Industrial-type engines include both those with basic automotive configurations and those designed specifically for industrial use – usually smaller than the automotive types. Applications of industrial-type engines include light marine propulsion; light farm, construction, and industrial uses; and standby or emergency stationary power generation. Aircraft reciprocating engines are designed specifically for light weight, reliability, and operability at various attitudes and altitudes; they are seldom used for other applications. The combustion process and the emission characteristics of all these engines are similar.

Single-cylinder 4-cycle gasoline engines are usually built with more rudimentary induction and ignition systems than the multicylinder engines. Therefore, while the combustion process is basically the same, the emission characteristics are probably somewhat different because less control is exerted over air-fuel ratio and ignition timing. These engines are used for garden, recreational, and very light industrial applications.

Small 2-stroke-cycle gasoline engines have markedly different emission characteristics for two basic reasons. First, the products of combustion are scavenged out of the cylinder by unburned air-fuel mixture; because this process is inherently inefficient, some raw fuel finds its way into the exhaust. Second, lubricating oil is generally mixed with the gasoline, which creates a characteristic "haze" in the exhaust. In some 2-cycle engines, the lubricating oil is force fed from a separate reservoir. In either case, the oil or its products of combustion are present in the exhaust gases. Two-cycle engines are used as outboard motors and for motorcycles, light hand tools, and garden and very light industrial applications.

Rotary engines such as the *Wankel* differ somewhat from piston engines in emission characteristics because of the substantially different shape of their combustion chambers. In addition, there is a blow-by path past the apex seals directly into the exhaust which is not present in reciprocating engines (except those with a leaking exhaust valve).

Stratified-charge engines are spark ignited, but do not operate with a homogeneous fuel-air charge. Instead, the fuel is injected in-cylinder in some manner so as to achieve a localized combustion region in part of the combustion chamber. Such engines are operated unthrottled over at least part of their load range, and overall fuel-air mixtures are very fuel-lean at light loads. Some of these engines have a multifuel capability. First-cost considerations have so far inhibited any general use of this type of engine.

Gaseous-fueled SI engines of various types are in use in small numbers, operating on natural gas or LPG fuel. Operating characteristics are similar to those of gasoline-fueled engines. It is possible to run natural-gas-fueled engines exceptionally lean; under these conditions, the exhaust can be substantially cleaner (and less reactive) than that of gasoline-fueled engines.

In general, the points which will be made in the discussion of gasoline-engine combustion phenomena are applicable to all types of gasoline engines; however, with 2-cycle and stratified-charge engines additional factors are significant.

Diesel Engines

Diesels operate on heavier distillate fuels or on residual fuels. Fuel is injected in-cylinder and the combustion process is heterogeneous and initiated by compression ignition; more specifically, compression ignition takes place as a result of the high temperature of the air charge that is produced by the compression process.

Diesel engines are manufactured in a number of varieties; the following paragraphs describe some of the principal features that characterize them.

Both **2-cycle- and 4-cycle-type diesels** are available; the differences in the combustion process and the emission characteristics are distinguishable but not markedly different.

Turbocharged diesels use an exhaust-gas-driven dynamic compressor-turbine unit (turbocharger) to increase the rate of air flow through the reciprocating unit. As a result, combustion occurs at a higher pressure and generally with a leaner fuel-air ratio than in **naturally aspirated engines.** However, mismatches of speed between the reciprocating engine and the turbocharger during speed/load transients can cause momentary over-rich operating conditions.

Direct-injection diesels have an injector that sprays fuel directly into the cylinder. Usually the injector is centrally located; the fuel spray pattern is symmetrical; and the piston crown is contoured to give the desired combustion-chamber shape. **Precombustion-chamber diesels** have an ancillary chamber closely connected to the main cylinder. Fuel injected into the precombustion chamber is expelled at high velocity into the main combustion chamber.

Discussions of diesel-engine combustion that follow in this chapter are generally applicable to all types of diesel engines.

POLLUTANTS OF PRINCIPAL CONCERN

Gasoline-Engine Emissions

The gasoline-engine pollutant emissions of principal concern are CO, HC, NO_X, PNA, lead, and other particulates. Unmodified fuel molecules are a minor constituent of the gaseous hydrocarbon emissions, which are primarily light paraffins and olefins, along with traces of aromatics, aldehydes, and other oxygenates. Smoke emissions are not presently of major concern. Some odor is characteristic of gasoline-engine exhaust; however, this odor is not generally considered a pollutant of great concern.

Diesel-Engine Emissions

The diesel-engine pollutant emissions of principal concern are smoke, CO, HC, PNA, odor, and NO_X. A large portion of the diesel-engine hydrocarbon emissions are unmodified fuel molecules. Emissions of CO from diesels are very low compared with the emissions from gasoline engines. Smoke and odor are highly noticeable and consequently cause public complaint. Since specifications for sulfur content of diesel fuels are not as stringent as for gasoline, diesels may emit small amounts of SO_X; however, these emissions are not presently of great concern.

EMISSION LEVELS FROM IC-ENGINE COMBUSTION PROCESSES

The following discussion summarizes the current state of the art regarding emissions from IC-engine combustion processes, covering gasoline engines and diesel engines separately.

GASOLINE ENGINES

Emission Levels for Present-Production Gasoline Engines

Gasoline-engine emission levels vary substantially with the mode of operation. It is now common practice to use composite emission levels averaged over a driving cycle to represent output of automotive engines. No such practices have been established for the rest of the gasoline-engine population.

Emission levels from new **automotive engines** have been subject to Federal regulation since 1968; consequently, Federal standards can be used to characterize present emission levels. These are presented in Table VII-2.

Table VII-2. Federal Standards for New Light-Duty Vehicle Emissions*

(g/mi)

Pollutant	Pre-1968 Uncontrolled	1968 Stds**	1970 Stds
HC	11.5 *(900 ppm)*	3.3 *(275 ppm)*	2.2 *(180 ppm)****
CO	80 *(3.5%)*	35 *(1.5%)*	23 *(1.0%)****
NO_x	5.9 *(1500 ppm)*	–	–
Particulate	0.3	–	–

*Composite levels for a Federal 7-mode driving cycle.
**Converted to mass emission levels for a 4000-lb vehicle.
***Converted to concentration levels for a 4000-lb vehicle.

Power levels during the Federal 7-mode cycle are below 20 hp; consequently, the values in Table VII-2 do not represent the emission levels from highly loaded heavy-duty industrial engines.

Multicylinder industrial engines operating at higher loads generally emit higher concentrations of NO_x and somewhat lower HC. CO emissions are affected more by fuel-air ratio than by load; consequently, CO levels are strongly influenced by carburetion. The following tabulation gives emission levels that are assumed to be characteristic of highly loaded constant-speed engines.

Emission Levels for Highly Loaded Constant-Speed Gasoline Engines

Pollutant	Concentration	Mass, g/hp-hr
HC	100-200 ppm	1.7 - 3.4
CO	1-2%	30 - 60
NO_x	2000-4000 ppm	10 - 20

Emissions of NO_x vary with manifold vacuum, compression ratio, ignition timing, and fuel-air ratio, and they can range as high as 5000 ppm.

No data were found for large industrial types of spark-ignited engines using natural-gas fuel; however, on the basis of laboratory single-cylinder engine tests(1), it can be assumed that NO_x emissions may be as high as 10 to 15 g per hp-hr. HC and CO emission levels will be strongly influenced by carburetion.

Small crankcase-scavenged 2-cycle engines tend to emit very high concentrations of HC. In one study of 2-cycle motorcycle engines(2), the following composite emission levels were observed in driving-cycle tests.

Emission Levels for 2-Cycle Engines in a 7-Mode Driving Cycle

Pollutant	Concentration
HC	2000 - 6000 ppm
CO	1.5 - 7.5%
NO_x	100 - 500 ppm

Emission Levels Attainable With Latest Technology for Gasoline Engines

Gasoline-engine emission levels attainable with the latest technology are difficult to estimate for two reasons: (1) the technology has been moving fairly rapidly and (2) engine manufacturers are hesitant to reveal data or forecasts regarding attainable levels. Further, in many instances, emission levels can be reduced by compromising performance; in these cases, attainable levels are set by deciding how large a performance degradation is acceptable.

Hydrocarbons. Emissions of HC can be reduced by combustion-chamber design to minimize crevices and quench spaces. Moderately lean fuel-air mixtures, retarded ignition timing, and lower compression ratio also tend to reduce HC emissions, but these involve making some performance compromises. There are no established minimum levels of HC emission attainable with present technology; however, concentration levels below 50 ppm are probably attainable under ideal conditions.

Carbon Monoxide. With respect to CO, single-cylinder studies(3) have demonstrated that concentration levels on the order of 0.1 percent can be achieved at constant speed with moderately lean mixtures. There are no established minimum levels of CO emission attainable in a driving cycle with present technology.

Oxides of Nitrogen. Reductions in NO_x emissions of up to 75 percent have been demonstrated during a driving cycle with the use of exhaust-gas recirculation (EGR), the resulting composition NO_x concentration level being about 400 ppm.(4) There is, however, some question as to whether this amount of recycle (about 15 percent) permits satisfactory driveability. Further, EGR can be used only at part-load; therefore, it is less suitable for use with engines in nonautomotive applications that operate continuously at high load. Emissions of NO_x from highly loaded engines can be reduced to some extent by retarded ignition timing(5), with some sacrifice in performance.

In general, NO_x levels from gasoline engines can be reduced, particularly at part load, but such reductions involve a trade-off with performance. The optimum trade-off has not been established.

Emission Goals for Gasoline Engines

Goals have been established for composite driving-cycle exhaust emissions from future automotive-type vehicles. Alternative controls, such as catalytic or thermal reactors, may be more significant than combustion modifications in meeting these goals.

Several sets of research goals have been used by NAPCA in the past, and Federal Standards for 1972, 1975, and 1980 light-duty vehicles have been established previously. However, new Federal Standards for HC, CO, and NO_x, established by the 1970 Amendment to the Clean Air Act, now supersede both research goals and proposed standards previously set by NAPCA for 1975 and later.

The 1972 standards, as described in the November 10, 1970, Federal Register, are based on a new driving schedule, a new exhaust sampling procedure, and different instrumentation from that specified for the 1970 Federal Standards. As a result of these changes, a direct comparison between standards for 1970 and 1972 is not possible, although conversion factors have been established.

Federal Standards for 1972 and later are given below, along with a comparison with 1970 standards using DHEW's conversion factors.

Present and Future Federal Standards for Composite Emissions from Light-Duty Vehicle Engines on a Driving Cycle, g/mi

Pollutant	1970 Stds	1970 Vehicle, 1972 Procedure	1972 Stds	1975 Stds	1976 Stds
HC	2.2	4.6	3.4	0.46	0.46
CO	23	47	39	4.7	4.7
NO_x	–	–	–	–	(0.4)

The value shown above for the 1976 NO_x standard is in parentheses to indicate that this standard has not been established as of this writing, but it is expected to be about 0.4 or 0.5 g per mi. A value of 0.03 g per mi for particulate emissions has been used previously as a 1980 NAPCA goal.

There are no similar standards or goals for gasoline engines in other applications. Combustion modifications or use of control devices developed for automotive engines may or may not be feasible for nonautomotive applications.

It would be unrealistic to expect that gasoline-engine emission levels, even with major combustion-process modifications, could be made as low as those for external combustion units. However, such levels should be considered as a theoretically possible limit.

DIESEL ENGINES

Emission Levels for Present-Production Diesel Engines

As with gasoline engines, diesel-engine emissions vary substantially with the mode of operation. A range of emission levels characteristic of present diesels is given in the following tabulation.

Characteristic Emission Levels for Diesel Engines at Constant Speed*(6-9)

Pollutant	Idle	Full Load
HC, ppm	20 to 300	150 to 1000
CO, percent	0.01 to 0.1	0.03 to 0.3
NO_x, ppm	200 to 400	750 to 2500

*Not corrected for CO_2.

Since the diesel operates typically with fuel-air ratios in the range of 0.01 to 0.05, correction factors for CO_2 (i.e., for equivalent concentrations at stoichiometric fuel-air ratios) range from about 1.3 at full power to nearly 10 at idle.

The broad range of emission levels given above reflects the difference in emissions from different types of diesels: 2-cycle vs. 4-cycle, turbocharged vs. naturally aspirated, and direct-injection vs. precombustion-chamber injection. An outstanding characteristic of diesel emissions is the low CO level.

Other highly noticeable characteristics of diesel engines are odor and smoke. Presently, there are no absolute scales for the measurement of diesel exhaust odor; however, there are a number of smoke-level ratings available. Diesel engines for motor vehicles are now subject to Federal regulations which allow:

- 40 percent opacity during the engine acceleration mode
- 20 percent opacity during the engine lugging mode.

Opacity in this instance is measured with the U.S. Public Health Service Smokemeter.(10)

Emission Levels Attainable With Latest Technology for Diesel Engines

Recent reductions in diesel engine emission levels have been brought about through fuel-injector improvements – elimination of fuel dripping from the injector after the main injection period has been an important factor in direct-injection engines. The effect of such modifications has been to shift emission levels toward the lower end of the range shown above.

Further reductions in certain emissions, particularly NO_X and smoke, are possible by derating engines. However, manufacturers and users both have had strong incentives not to use this approach.

Emission Goals for Diesel Engines

Appropriate goals for diesel-engine emissions appear to be the following:

- Elimination of detectable odor and visible smoke
- Reduction of NO_X to levels approaching that which would be obtained by combustion of very lean homogeneous fuel-air mixtures
- No increase in CO levels.

Although there is no firm technical basis on which to demonstrate that these goals are attainable, there is a rationale for expecting that major improvements are possible: the diesel operates with moderate to large amounts of excess air with which low smoke and NO_X are achievable in other combustion configurations; also, with a nonpremixed fuel-air charge, wall-quench effects can ideally be avoided.

Inhomogeneity in the fuel-air charge makes the compression-ignition process feasible but also results in high smoke, odor, and NO_X. A general goal should be to modify the injection-combustion process as far as possible to minimize the contribution of inhomogeneity to high emissions.

GAPS IN NEEDED R&D TO REDUCE ENGINE EMISSIONS BY COMBUSTION-PROCESS MODIFICATION

Gasoline-Engine R&D Gaps

Gasoline-engine combustion is well understood as compared with many other types of combustion. This is mainly because of the possibility of assuming a homogeneous premixed fuel-air charge in analytical investigations. The actual mechanism of hydrocarbon-O_2 oxidation in gasoline engines is only partly understood; fortunately, however, an understanding of this mechanism is not presently essential as far as emission reduction problems are concerned. (The hydrocarbon-O_2 system has been studied primarily in relation to its influence on preignition, autoignition, and related phenomena in gasoline engines.)

CO and NO

Satisfactory predictions of the observed levels of CO and NO_X in engine exhaust have been derived on the basis of analytical investigations of the kinetics of the expanding products of combustion in an engine cylinder by Newhall(11) and Keck(12). These investigations covered stoichiometric or lean fuel-air ratios. Analytical predictions for fuel-rich mixtures have been less successful; however, the CO and NO emissions can be predicted with reasonable accuracy using the extensive experimental data available. Lack of knowledge about the kinetics of the $HC\text{-}O_2\text{-}N_2$ system represents a gap in our understanding of gasoline combustion, but such knowledge does not appear at present to be essential for reduction of emissions.

HC

Unburned HC in the exhaust has been shown to be largely the result of wall quenching or because of crevices in the combustion chamber where combustion does not take place.(13-15) Investigations of the wall-quench phenomenon(16-18) have not been completely successful, although empirical expressions for the appearance of wall-quenched HC as a function of cylinder temperature and pressure have been derived(15). Further work on wall quenching appears to be needed to gain more complete information concerning the effects of engineering and operating variables on the appearance of unburned HC; however, great reductions in emission levels are not expected to result from such work.

The potential effect of lubricating oil on cylinder walls on HC emission has been largely ignored. This has been justified on the basis that oil consumption in modern engines is generally too low to contribute significantly to HC emissions. However, in light of proposed 1980 auto standards, emissions derived from lubricating oil could be more significant, particularly if the response of these emissions to thermal or catalytic reactors is different from that of fuel-derived exhaust HC.

Particulates and PNA

The characteristics of particulate and PNA emissions and their sources and formation have been under investigation for some time(19-21); however, this work is not complete, and further work is needed.

Fuel Effects

It has long been recognized that substitute or modified fuels can substantially affect engine emissions. For example, hydrogen used as a fuel does not produce any HC or CO emissions. However, cost, supply, handling, storage, and engine-derating factors are all against the use of H_2. Other fuels, such as methane, can produce moderate benefits and have fewer disadvantages. No alternative fuel appears practical for use at present as a nationwide substitute for gasoline. However, there does not appear to be any basis for concluding that a practical, low-emission substitute for gasoline can never be found. Consequently, it appears reasonable to continue to consider the use of an alternative fuel as an R&D opportunity that could be significant in reducing emissions. However, the probability of economic and practical success for this approach is considered low.

Possible modifications of gasoline fuel to reduce emissions have been investigated extensively(22). The effect of fuel composition on the amount and reactivity of HC emissions is currently being studied by a number of organizations. While such investigations are justifiable, particularly as conducted by fuel suppliers, the expected gains are not large, at least in terms of effective HC emission reductions. The effect of fuel variables on particulate and PNA emissions is more direct, but appears to have received less study; thus, this is considered an R&D gap at present.

Effects of Engineering Variables

The effects of most engineering variables on emission levels have been investigated extensively(23). One exception to this is lean-mixture operation. There is sufficient information available to indicate that major reductions in NO_x emissions are possible with the use of ultralean fuel-air mixtures; however, the limits of the potential reduction have not been established, and there is also a question as to how ultralean mixtures affect HC emissions(24). Consequently, further investigations of lean-mixture operation of gasoline engines are needed.

A necessary adjunct to the investigation of lean-mixture operation, and a current R&D gap, is information on the effect of mixture preparation (degree of homogeneity and fuel atomization, and the amount of fuel vaporization) on combustion and emissions. There is reason to expect that mixture preparation may have a significant effect on lean-mixture combustion and combustion limits.

A related area of work, although not combustion research in itself, is the development of fuel-induction systems capable of providing uniform distribution of fuel to the individual cylinders of multicylinder engines. Improved induction systems will be needed if practical lean-mixture engines are to be developed.

Combustion-Process Modifications

Certain modifications to the conventional gasoline-engine combustion process can result in reduced emissions. Two principal examples are exhaust-gas recirculation (EGR) and stratified-charge engines. The potential benefits of EGR have been demonstrated, and device development associated with EGR has established practical recycle levels and has proved out the durability of the system.(4)

Stratified-charge engines have been under investigation for at least 25 years, but only recently have they been looked at as a possible low-emission engine.(25,26) This work has been generally encouraging, and further study of the potential of stratified-charge engines appears justified.

Other combustion-process modifications could lead to similar or greater reductions in gasoline-engine emissions(27). Promising novel concepts in this area should be considered potentially deserving of R&D support.

Characterization of Exhaust Emissions

Studies to characterize various emissions from engine sources are conducted for two reasons: (1) to aid in understanding the combustion process and (2) to evaluate the significance of the engine as a source of air pollution. For purposes of this study, only those emission-characterization studies having the former objective are considered to be combustion R&D. Examples of needed R&D of this kind include the further study of particulate and PNA emissions, as has been mentioned previously.

Most NAPCA programs to characterize emissions appear to have the second objective. This work is needed, but not considered part of combustion R&D as covered in this report.

Diesel-Engine R&D Gaps

The diesel-engine combustion process is not well understood, compared with the knowledge of gasoline-engine combustion. This is because of the heterogeneous nature of the combustion process. The fuel-injection, mixing, vaporization, ignition, and combustion processes that take place are extremely complex and difficult to describe mathematically.

Ignition delay and rate of heat release have been of principal interest in the past, and empirical models for these phenomena have been formulated(28). Vaporization, ignition, and combustion of fuel droplets have also been studied, but with less success(28). Some understanding of smoke formation has been gained(29), and research on odor formation has tended to support the theory that odorous exhaust emissions are produced by partial oxidation in regions too lean to burn at the start of combustion(30). However, efforts to identify the actual compounds that cause the characteristic diesel-exhaust odor have been only partly successful to date.(31)

The development of a realistic fuel-mixing and vaporization model for diesel combustion appears to be a significant R&D step that is fundamental to further diesel research. The result of this work, if successful, would be the ability to predict fuel-concentration, temperature, and pressure levels within the cylinder as a function of time and position. Related R&D gaps are: the identification of the odor-producing constituents of diesel exhaust, and further understanding of pyrolysis in fuel-rich regions and nonflame reactions in fuel-lean regions.

The principal objective of work in the diesel R&D gaps mentioned above is to gain insight as to possible modifications to the diesel combustion process that will result in reduced emissions. While the heterogeneous nature of this process makes it difficult to investigate, it also allows great latitude for innovation in the way the fuel is introduced and burned.

It is recognized that the desired combustion-process modifications need not spring from a detailed understanding of the combustion phenomena, but may also be the result of intuitively derived concepts. Both approaches are considered to be part of the needed combustion R&D in the diesel-engine field.

SUMMARY OF CURRENT AND RELEVANT COMBUSTION R&D

Gasoline Engines

Most of the combustion research relating to gasoline-engine exhaust emissions is being conducted by private industry, and is aimed principally at multicylinder, 4-stroke-cycle automotive type engines. This research is generally applicable to the entire population of gasoline engines.

The automobile manufacturers, oil companies, and additive-chemical companies are the principals in this research, and the scope of their programs is considered proprietary. Combustion research in this area is also conducted by cooperative industrial groups and trade associations, principally the Inter-Industry Emission Control Program(32) (initially the Ford-Mobil program), the Chrysler-Esso Program, the American Petroleum Institute, and the Coordinating Research Council(33). Limited information on the scopes of these programs has been made public, but many technical details have been considered proprietary; publication of some of these results is expected eventually.

A substantial amount of the literature and information available on gasoline-engine combustion has been contributed by the private sector, but such publications do not generally cover programs currently under way.

Funding for the entire private-sector gasoline-engine emission-control program is estimated to be on the order of several hundred million dollars annually. There is no breakdown available on the amount of this work that can be considered gasoline-engine combustion R&D, but it is expected that it would not exceed one-third or one-quarter of the entire program.

Gasoline-engine combustion R&D is being conducted by the Government through agencies such as the Bureau of Mines and Department of Defense as well as APCO. Reference 34 describes both combustion R&D and alternative-control research under way through Federal agencies.

Diesel Engines

Combustion research related to diesel-engine emissions is conducted by engine manufacturers, oil companies, and the Government; this work has not reached the proportions of the gasoline-engine research work. It can be assumed that most of the research being conducted by private industry is being done by manufacturers of engines for over-the-highway application.

Summary of Current R&D

Tables VII-3 and VII-4 present a summary of gasoline-engine and diesel-engine combustion-research projects under way, on which some information is available.

Table VII-3. Current Combustion R&D – Gasoline Engines

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-a	Gasoline composition & vehicle exhaust gas PNA content	NAPCA-DCP CPA 70-104 CPA 22-69-56 CRC CAPE-6-68	Essu Res. & Eng. Co. Linden, N. J.	G. P. Haas	Effect of fuel comp., engine operating variables, and emission control system on PNA emission rate	50,603 (FY '70) 32,879 (FY '69)
VII-b	Emission reduction using gaseous fuels for vehicular propulsion	NAPCA-DCP CPA 70-69	Inst. of Gas Technology Chicago, Ill.	–	Determine pollutant emissions for engines fired with gaseous fuels	68,994 (FY '70)
VII-c	Selected R&D of nitrogen oxides control methods for stationary sources	NAPCA-DCPE CPA 70-90 PH 22-68-55	Esso Res. & Eng. Linden, N. J.	W. Bartok	Characterization & control of NO_x from stationary IC engines	363,025 (FY '70)
VII-d	Effects of fuel and engine variables on the characteristics of particulate emissions in automotive exhaust	NAPCA-DCP CPA 22-69-145	Dow Chemical Co. Midland, Mich.	J. B. Moran	Relationship of fuel additive to particulate emission composition & nature	230,886 (FY '70) 104,000 (FY '69)
VII-e	Study of emissions from two-cycle engines	NAPCA-DMVR&D CPA 22-69-91	Olson Labs. Dearborn, Mich.	H. J. Wimette	Characterize motorcycle engine emissions	961 (FY '70) 10,941 (FY '69)
VII-f	Study of influence of fuel atomization, vaporization, and mixing processes on pollutant emissions from motor vehicle power plants	NAPCA-DMVR&D CPA 70-20	Battelle Memorial Inst. Columbus, Ohio	F. A. Creswick	Develop induction system for lean-mixture operation	89,150 (FY '70)
VII-g	Study of exhaust emissions from reciprocating aircraft power plants	NAPCA-DMVR&D CPA 22-69-129	Scott Res. Labs. Plumsteadville, Pa.	W. Zegel	Measurement of CO, HC, and NO_x under various flight modes	1,075 (FY '70) 89,650 (FY '69)
VII-h	Design criteria for hydrogen burning engines	NAPCA-DMVR&D EHS 70-103	Oklahoma State Univ. Stillwater, Okla.	R. Schoeppel	Develop a hydrogen burning engine and determine emissions	55,815 (FY '70)
VII-i	Decomposed methanol as a low emission fuel	NAPCA-DMVR&D EHS 70-118 CPA 22-69-70	Univ. of Santa Clara (FY '70) Consolidated Eng. Tech., Inc. Mountain View, Calif. (FY '69)	R. Pefley M. Saad	Study emissions from CFR engine running on $CO:2H_2$	27,486 (FY '70) 42,269 (FY '69)
VII-j	Control of NO_x emissions from mobile sources	NAPCA-DMVR&D EHS 70-122	Bendix Res. Labs. Southfield, Mich.	D. Bernard	Fuel injection with lean mixtures	105,102 (FY '70)
VII-k	Exhaust emissions from uncontrolled vehicles and related equipment using internal combustion engines	NAPCA-DMVR&D EHS 70-108	Southwest Res. Inst. San Antonio, Texas	C. T. Hare K. Springer	Determine emissions from selected uncontrolled mobile sources	88,452 (FY '70)
VII-l	Study of relationship of engine deterioration to exhaust emissions	NAPCA-DMVPC CPA 22-69-140	Automotive Res. Assoc., Inc. San Antonio, Texas	–	–	48,868 (FY '69)

Table VII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-m	A feasibility study on the control of nitrogen oxides in automotive engine exhaust	NAPCA-DMVPC CPA 22-69-89 PH 86-67-25	Esso. Res. & Eng. Linden, N. J.	D. Wade D. G. Levine W. Glass	Exhaust-gas recirculation	98,180 (FY '69)
VII-n	Study of the interactions of fuel volatility and automotive design as they relate to driveability	NAPCA-DMVR&D CPA 22-69-66 CRC CAPE-4-68	Ethyl Corp. Ferndale, Mich. Also Bureau of Mines Bartlesville, Okla.	R. Kerley	Determine interactions of fuel volatility and automotive design on driveability	62,348 (FY '69)
VII-o	Heavy duty vehicle emissions	NAPCA-DMVPC PH 86-67-72	Southwest Res. Inst. San Antonio, Texas	–	Measurement of emissions from 10-24,000 lb GVW gasoline-engine-powered trucks	(FY '70) 57,814 (FY '69) (FY '68) 174,634 (FY '67)
VII-p	Aromatic by-products of combustion	NAPCA-ORG AP 00275	Univ. of California Berkeley, Calif.	B. D. Tebbens J. F. Thomas M. Muki	Study formation of PNA compounds and fate once airborne	52,561 (FY '70) 50,297 (FY '69) 45,066 (FY '68)
VII-q	Reduction of polycyclic aromatic hydrocarbons	NAPCA-ORG AP 00323	Univ. of Birmingham England	R. Long	–	7,675 (FY '70) 4,290 (FY '69) 7,600 (FY '68)
VII-r	Carburetors, reduction of engine exhaust emissions	NAPCA-ORG AP 00365	Univ. of Michigan Ann Arbor, Mich.	J. A. Bolt D. L. Harrington S. Derezinski	Reduction of carburetor metering errors	55,629 (FY '70) 50,492 (FY '69) 103,968 (FY '68) (FY '67)
VII-s	Combustion gas composition	NAPCA-ORG AP 00385	Univ. of California Berkeley, Calif.	E. S. Starkman	Mechanisms of formation of combustion-generated air pollution precursors	140,229 (FY '69) 103,968 (FY '68) 50,157 (FY '67) 34,999 (FY '66)
VII-t	Engine emission reduction by combustion control	NAPCA-ORG AP 00560	Penn. State Univ. University Park, Pa.	W. E. Meyer	Inv. the effect of heterogeneous flame propagation on HC & CO emissions	50,238 (FY '70) 52,262 (FY '69) 40,107 (FY '68) 50,686 (FY '67)
VII-u	Combustion process analysis	NAPCA-ORG AP 00582	Univ. of Wisconsin Madison, Wis.	H. K. Newhall	Kinetics of CO & NO formation	36,816 (FY '70) 18,888 (FY '69) 14,713 (FY '68) 27,865 (FY '67)
VII-v	Kinetics of nitrogen-oxide automotive pollution	NAPCA-ORG AP 00763	Univ. of Washington Seattle, Wash.	A. Hertzberg R. C. Corlett A. T. Rossano D. A. Russell	Shock-tube simulation of engine processes	47,877 (FY '70) 58,169 (FY '69) 63,019 (FY '68) (FY '67)

Table VII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-w	Kinetics of nitric oxide at high temperatures	NAPCA-ORG AP 00858	Drexel Inst. Tech. Philadelphia, Pa.	R. A. Matula	–	35,916 (FY '70) 46,526 (FY '69)
VII-x	Non-equilibrium effects in internal combustion engine	NAPCA-ORG AP 00871	Cooper Union New York, N. Y.	W. Chinitz	–	9,825 (FY '70)
VII-y	Characteristics and photochemical reactivity of fuel components and combustion products	NAPCA-DCP Interagency transfer	Bureau of Mines Bartlesville, Okla.	B. Dimitriades H. B. Carroll T. C. Wesson J. E. Payne J. M. Clingenpeel	Photochemical reactivity of auto-engine exhaust compounds	180,000 (FY '70)
VII-z	Interactions between fuel compositions and engine factors influencing exhaust emissions	NAPCA-DMVR&D Interagency transfer	Bureau of Mines Bartlesville, Okla.	J. R. Allsup B. Dimitriades T. C. Wesson R. W. Hurn H. B. Carroll W. F. Marshall	Relationship of combustion products to fuel composition and combustion-process variables	145,000 (FY '70)
VII-aa	Products of combustion of distillate fuels for motive power	NAPCA-DMVR&D Interagency transfer	Bureau of Mines Bartlesville, Okla.	R. W. Hurn	–	185,000 (FY '70)
VII-bb	Ford combustion process (hybrid)	NAPCA-DMVPC U. S. Army Tank Auto. Command DAAE 07-68-C-0880	Ford Motor Co. Dearborn, Mich.	A. Simko	Low-emission stratfield-charge engine	407,000 (FY '69)
VII-cc	Fuels combustion research	Bureau of Mines	Bureau of Mines Bartlesville, Okla.	R. W. Hurn J. A. Tipton	Effect of fuel and engine variables on nature of exhaust emissions (both gasoline and diesel engines)	–
VII-dd	Effect of fuel volatility on automotive emissions	Bureau of Mines	Bureau of Mines Bartlesville, Okla.	B. H. Eccleston B. H. Noble J. E. Payne H. B. Carroll J. M. Clingenpeel B. Dimitriades D. L. French T. C. Wesson	Effect of light-end volatility changes on exhaust emissions	–

Table VII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-ee	Texaco combustion process	U. S. Army Tank Auto. Command	Texaco Res. Labs. Beacor, N. Y.	E. Mitchell	Stratified-charge engine	–
VII-ff	Effects of gasoline properties on exhaust emissions caused by combustion-chamber deposits	Coordinating Res. Council CAPE-3-68	Industry Labs.	–	Effect of gasoline props. and additives	–
VII-gg	Nature of the physical-chemical characteristics of the particles associated with PAH present in automobile exhaust	Coordinating Res. Council CAPE-12-68	Battelle Memorial Inst. Columbus, Ohio	C. Melton W. M. Henry	Collection & characterization of exhaust particulates	–
VII-hh	Combustion process analysis	State of California	Univ. of California Los Angeles	L. B. Robinson J. O. Pinkerton	Study formation of exhaust-gas pollutants	–
VII-ii	Combustion process control	State of California	Univ. of California Los Angeles	R. D. Kopa	Effect of water injection; effect of wall deposits; molecular beam sampling	–
VII-jj	Emission reduction for spark-ignited outboard engines	Outboard Marine Corp.	Univ. of Michigan Ann Arbor, Mich.	D. Cole	Characterization & reduction of emissions	–
VII-kk	LNG vehicle	San Diego Gas & Electric Co.	San Diego Gas & Electric Co. San Diego, Calif.	–	–	–
VII-ll	Combustion and exhaust emission of automobile gasoline engine during acceleration	Japan Automobile Res. Inst.	Waseda Univ. Japan	T. Saitoh	–	–
VII-mm	The influence of mixture condition on nitrogen oxide emissions from automotive gasoline engines	Nisson Motor Co., Ltd.	Eng. Labs, Nisson Motor Co. Yokosuka, Japan	H. Kuroda Y. Nakajima	Influence of inlet air condition, mixture condition, and exhaust-gas recirculation	–
VII-nn	Effect of mixture quality and combustion chamber configuration on exhaust emission	Motor Ind. Res. Assoc. (U. K.)	Motor Ind. Res. Assoc. Warwickisfire, England	A. E. Dodd Z. Holubecki I. D. Lytollis	Single-cylinder engine	–
VII-oo	–	–	Mobil Oil Co. Ltd. Res. & Tech. Serv. Lab. Stanford-le-Hope, Essex, England	J. H. Boddy	Studies on exhaust gas recirculation and the related effects on fuel quality on vehicle exhaust emissions	–
VII-pp	–	–	Univ. of Strathclyde Dept. of Pure & Applied Chem. Glasgow, Scotland	–	Studies on formation of nitrogen oxides in internal combustion engines	–

Table VII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-qq	–	–	Zenith Carburetor Co. Ltd. Dunstable, Beds, England	–	Studies in the reduction of emissions from automotive engines by modifications to carburetor and induction-manifold design	–
VII-rr	–	–	Institute for Piston Engines Langer Kamp, Germany	Dr. H. Müller	Effects of mixture preparation and operating conditions on vehicle exhaust gas composition and air injection	–
VII-ss	–	–	Institut Francais de Petrole France	M. Sale	Automotive emission reduction through development of stratified mixtures, exhaust gas recirculation, fuel injection, and fundamentals of NO_x formation	–
VII-tt	Analysis of vehicle emissions with emphasis on aromatic polycyclic hydrocarbons	National Res. Council, Italy	Stazione Sperimentale Per I Combustibili, Milano	A. Galtieri F. Casellato	Chromatographic and spectrophotometric analysis of PNA emissions	–
VII-uu	Determination of polycyclic aromatic hydrocarbons in engine exhaust	–	Univ. of Perugia Italy	A. Candeli V. Mastrondrea G. Morozzi	Effect of fuel and engine variables on PNA emissions	–

Table VII-4. Current Combustion R&D – Diesel Engines

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-vv	Diesel exhaust composition and odor	NAPCA-DMVR&D CPA 22-69-63 (CRC CAPE 7-68)	A. D. Little, Inc. Cambridge, Mass.	P. Levens	Analysis for odor-producing constituents of diesel exhaust using condensation, solvent, extraction, and liquid column chromatography	66,500 (FY '70) 33,263 (FY '69)
VII-ww	Single cylinder research engine operating in a diesel cycle	NAPCA-DMVR&D U. S. Army Tank Auto. Command DAA E07-69-C-1289	Univ. of Michigan Ann Arbor, Mich.	J. A. Bolt N. Henein	Effect of very high supercharge on emissions	44,450 (FY '70)
VII-xx	Study of chemical species in diesel exhaust and their contributions to exhaust odors	NAPCA-DMVR&D CPA 22-69-98 (CRC CAPE 7-68)	Illinois Institute of Technology Chicago, Ill.	A. Gaynor	Compound identification using GC and mass spec.	33,000 (FY '69)
VII-yy	Investigation of diesel powered vehicle odor and smoke	NAPCA-DMVPC PH 22-68-23	Southwest Res. Inst. San Antonio, Texas	K. J. Springer	Investigation of odor, smoke, HC, CO, and NO_x emissions and controls on diesel buses and truck tractors	237,578 (FY '69)
VII-zz	A field study of diesel engine exhaust	NAPCA-DMVR&D PH 22-68-36	Southwest Res. Inst. San Antonio, Texas	–	–	117,954 (FY '69)
VII-aaa	Control of NO_x, fuel injection-diesel engines	NAPCA-DMVR&D EHS 70-116	Northern Res. & Engr. Corp. Cambridge, Mass.	K. Bastress	Develop design parameters for control of NO_x in diesel engines	37,475 (FY '70)
VII-bbb	Liquid fuel ignition and combustion	NAPCA-ORG AP 00906	Rutgers Univ. New Brunswick, N. J.	R. L. Peskin	Basic mechanisms of ignition and combustion of droplets	36,385 (FY '68) 28,068 (FY '70)
VII-ccc	Fuel injection system analysis: diesel smoke reduction	NAPCA-ORG AP 00835	Univ. of Michigan Ann Arbor, Mich.	J. A. Bolt N. Henein	Computer simulation and exp. work to eliminate undesirable spray char	49,614 (FY '69) 29,319 (FY '70)
VII-ddd	Diesel fuel combustion chemistry as related to odor	NAPCA-ORG AP 00576	Drexel Inst. of Technology Philadelphia, Pa.	R. A. Matula	–	29,863 (FY '70) 53,589 (FY '69) 25,912 (FY '68)
VII-eee	Composition, smoke, and odor of diesel combustion products	Bureau of Mines	Bureau of Mines Bartlesville, Okla.	W. F. Marshall R. W. Hurn J. W. Vough D. J. Veal	Effect of fuel comp, engine design, and operating parameters on smoke, odor, and other emissions	–
VII-fff	Correlation of trace diesel exhaust products with engine operation	Bureau of Mines	Bureau of Mines Pittsburgh, Pa.	R. W. Freedman H. A. Watson	Evaluate toxic components in diesel exhaust in addition to major constituents	–
VII-ggg	Internal combustion engine simulation	U. S. Army Tank Auto. Command	Univ. of Wisconsin Madison, Wis.	P. S. Myers O. Uyehara	Computer simulation and correlation of exhaust smoke	–

Table VII-4. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VII-hhh	Compression-ignition engine combustion phenomena	U. S. Army Aberdeen Proving Gd.	Southwest Res. Inst. Army Coating Chem. Lab. San Antonio, Texas	R. D. Quillian	Basic studies of CI process; effect of fuel properties	–
VII-iii	Investigation of transient diffusion flame phenomena in a diesel engine combustion chamber	Caterpillar Tractor Co.	Univ. of Illinois Urbana, Ill.	W. L. Hull E. K. Buxholz	Investigation of precombustion chamber phenomena under high supercharge	–
VII-jjj	Search for analytical procedures covering diesel exhaust fumes and a method for measuring the oxygenated hydrocarbons in the fumes	Ontario Dept. of Energy Resources Management	Univ. of Waterloo Waterloo, Ontario Canada	F. W. Karasek	Chem. analysis of oxygenated organic components in diesel exhaust	–
VII-kkk	Control of exhaust smoke by fuel additives in automobile diesel engines	Japan Automobile Res. Inst., Inc.	Waseda Univ. Japan	M. Nabetani T. Saitoh	Mechanism of smoke formation and its control	–

R&D OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Eleven R&D opportunities directed toward reduction of emissions from reciprocating IC engines are recommended. Six of these are related to gasoline-engine combustion, three to diesel, and two generally applicable to both gasoline and diesel engines. These opportunities cover the following areas:

Gasoline Engines

- Stratified-charge engines
- Lean-mixture operation and mixture preparation
- Alternative fuels
- Generally applicable
  - wall quench
  - effect of lube oil
  - particulate and PNA formation

Diesel Engines

- Combustion-process modifications through better understanding of combustion processes

General

- Kinetics of NO_X formation in IC engines
- Novel concepts for combustion-process modification

In the case of exhaust-gas recirculation, no funding for FY 1971 through 1975 is recommended because it is believed that current APCO projects will have demonstrated the effectiveness of EGR systems and that any further work on EGR should be conducted with industrial funds. The remaining gasoline-engine combustion R&D opportunities are aimed either at the development of modified or unconventional combustion processes, or at gaining more basic information believed to be generally applicable to reducing gasoline-engine emissions.

The diesel-engine combustion R&D opportunities are all aimed at ultimately modifying the diesel fuel-injection and combustion process so as to minimize emissions. Two approaches to this are recommended: one using a more thorough understanding of the diesel combustion process to shed light on modifications that can be made to reduce emissions, the other stemming directly from ideas for combustion-process modifications for which there is some reason to expect that reduced emissions will be achieved.

These R&D opportunities are described on the following pages and their priorities summarized at the end of this chapter.

R&D Opportunity: VII-1

Related to: VII-bb, ee, ss

Support of Development and Evaluation of Stratified-Charge Gasoline Engines

Technical Objective and Approach

The objective is to investigate further the potential of producing low-cost stratified-charge engines for operation at low emission levels.

The approach should consist of supporting stratified-charge engine development programs with the additional funds needed for work on reducing emission levels.

Rationale and Incentive

Stratified-charge engines have been under development for at least 25 years, but only recently have their low emission possibilities become of interest.

These engines typically operate with in-cylinder fuel injection and with lean overall fuel-air ratios. Therefore, it is theoretically possible to lower substantially the effect of wall quenching on hydrocarbon emissions and, also, to achieve combustion at relatively low temperatures, thus achieving low NO_x emissions. However, the heterogeneous nature of the combustion process can lead to locally high-temperature zones and locally fuel-rich zones as well as to incomplete combustion in very lean regions. Thus, emission reduction possibilities may not be fully achieved. Present development efforts are showing promising results; therefore, support of these efforts appears justified.

Certain types of stratified-charge engines have a limited multifuel capability. Such engines, if practical for general automotive use, could eliminate the high-octane requirement of automotive gasoline and the use of lead additives.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $600-$1,500

R&D Time Range: 3 years

Recommended 5-year Funding, 1000's: $1,200*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	400	400	400	–	–	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines Plus Gas Engines

Relative Potential Benefit (overall rating): Very High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range		50-80	25-75			60-80	0-100			–
Expected		68	50			70	30			–
Fraction of ECC Emissions Affected		0.69	0.60			0.41	0.82			–
Noncombustion Controls Factor		.8	.8			.2	.8			–
Relative Potential Benefit Factor		9.38	6.00			22.96	4.92			43.26

Implementation Time, years: 3-8 most likely: 5

Relative Implementation Cost: Very Low

Relative Priority Rating: A

An explanation of the evaluation factors used in the priority ranking is contained in Chapter II and Appendix A.

R&D Opportunity: VII-2

Related to: VII-f, j

Development of Implementation Criteria for Lean-Mixture Operation of Gasoline Engines

Technical Objective and Approach

The objective is to further explore the incentive for developing engines that will operate on ultralean fuel-air mixtures and to develop basic information that will be useful in a hardware engine-development program.

The approach should include investigation of certain aspects of lean-mixture operation that require further study:

1. Establishing lean limits for good combustion. This limit will be affected by combustion-product residuals (and, therefore, manifold vacuum), mixture preparation, mixture motion, and possibly by ignition-system energy and timing. Possible effects of lean-mixture on octane-number requirements might also be investigated.
2. Establishing the effect on emission levels. Once the requirements for good combustion have been established, the real potential for emission reduction can be explored. If some increase in HC emissions is observed, it may be pertinent to determine whether wall quench, and the effect of lean mixtures on wall quench, is significant.
3. Definition of induction-system and ignition-system requirements for production engines. This work should establish a basis for follow-on hardware development.

Most of this work should be done with engines, perhaps initially with single-cylinder laboratory engines and eventually with multicylinder automotive engines, both using special induction systems to control closely the fuel-air ratio and the mixture state. Supporting work, such as bomb studies, might also be helpful for investigating some of the more fundamental aspects of this area and for separating the effects of different variables. As the results of any such study will be to some extent dependent upon the configuration of the equipment used, two parallel projects might be justified.

Rationale and Incentive

It is anticipated at present that reductions in NO_X levels to 80 to 95 percent of 1970 standards can be achieved by operating at fuel-air ratios of 0.05 (air-fuel ratio of 20:1) or leaner. Lean-mixture operation is expected to increase CO emissions. HC emission concentrations with present engines increase slightly with ultralean operation; however, there is some question as to whether this is a necessary result.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$660

R&D Time Range: 3 years

Recommended 5-year Funding, 1000's: $660*

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	260	200	–	–	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines Plus Gas Engines

Relative Potential Benefit (overall rating): High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range		0-50	0-50			50-95				
Expected		25	25			78				–
Fraction of ECC Emissions Affected		0.57	0.46			0.36				–
Noncombustion Controls Factor		.8	.8			.2				–
Relative Potential Benefit Factor		2.85	2.30			22.46				– 27.61

Implementation Time, years: 4-10 most likely: 8

Relative Implementation Cost: Medium

Relative Priority Rating: A

R&D Opportunity: VII-3 **Related to:** VIII-17, 18; VII-f, r, dd, mm, nn, qq, rr

Experimental Research on the Effect of Fuel-Air Mixture Preparation on Gasoline-Engine Emissions

Technical Objective and Approach

The objective is to determine the effect of fuel-air mixture preparation on the combustion process, on emission levels, and on the lean operating limit.

The approach should be to investigate various mixture-preparation variables including: degree of fuel atomization, degree of mixture homogeneity, relative amounts of fuel in liquid and vapor form, and time variations in these variables. The study should be conducted primarily with heavily instrumented single-cylinder engines.

Rationale and Incentive

This work is related to the recommended study of lean-mixture operation as more uniform mixing and distribution will be necessary for lean operation. However, it is listed separately because the results could be more generally applicable in that improved mixing and distribution will minimize local inhomogeneities that can contribute significantly to high emission levels.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$500 Recommended 5-year Funding, 1000's: $300
R&D Time Range: 3-5 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	100	100	–	–	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines
Relative Potential Benefit (overall rating): High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range		10-50	10-50			50-95	0-20			–
Expected		27	27			78	10			–
Fraction of ECC Emissions Affected		0.62	0.49			0.33	0.78			–
Noncombustion Controls Factor		.8	.8			.2	.8			–
Relative Potential Benefit Factor		3.35	2.65			20.59	1.56			28.15

Implementation Time, years: 4-8 most likely: 6 Relative Implementation Cost: Medium

Relative Priority Rating: A

R&D Opportunity: VII-4 Related to: VIII-4, 5; VII-nn

Analytical and Experimental Research on Gasoline-Engine Wall-Quench Phenomena

Technical Objective and Approach

The objective is to gain a better basic understanding of wall-quench phenomena and of the effect on emissions of important variables.

The approach should include single-cylinder engine studies, bomb studies, and steady-flow premixed flame studies of variables such as mixture ratio, mixture preparation, mixture motion, fuel composition, temperature and pressure, wall surface condition, and combustion-chamber shape.

Rationale and Incentive

Although this R&D opportunity represents a current knowledge gap, it is anticipated that most of the potential benefits have already been realized as the result of empirical studies of the effect of engineering variables on hydrocarbon emissions. Consequently, short-term gains, if any, would be moderate. Ultimately, however, such work will improve understanding of the mechanism of pollutant formation in IC engines, and the results could be more significant as further gains become more difficult to achieve.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$500 Recommended 5-year Funding, 1000's: $300

R&D Time Range: 3-5 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	100	100	–	–	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines Plus Gas Engines

Relative Potential Benefit (overall rating): Medium Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range			0-50							–
Expected			22							–
Fraction of ECC Emissions Affected			0.54							–
Noncombustion Controls Factor			.8							–
Relative Potential Benefit Factor			2.38							2.38

Implementation Time, years: 2-10 most likely: 5 Relative Implementation Cost: Low

Relative Priority Rating: C

R&D Opportunity: VII-5

Experimental Research on the Effect of Lubricating Oil on Gasoline-Engine Emissions

Technical Objective and Approach

The objective is to determine: (1) the form in which consumed oil appears in engine exhaust (i.e., how much is oxidized?) and (2) the effect of exhaust clean-up devices, such as thermal reactors or catalytic reactors, on lubricating oil or lubricating-oil combustion products in the exhaust.

The approach should include basic investigations as well as studies using single-cylinder and multicylinder engines.

Rationale and Incentive

The effect of lubricating oil on gasoline-engine emissions has been largely ignored in the past, probably because, even if all the oil normally consumed appeared as HC in the exhaust, the resulting contribution to emission levels would be minimal. A consumption rate of one quart per 4000 miles is equivalent to only 0.20 g per mi of hydrocarbons if no combustion takes place, less than one tenth of 1970 standards. However, in view of 1980 standards of 0.25 g per mi for hydrocarbons, oil could be far more important in the future.

While only minor HC reductions from 1970 levels could be anticipated to result from this study, this study would evaluate the importance of lubricating-oil control on emissions from the projected low-emission engines of the future.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $140-$300 **Recommended 5-year Funding, 1000's:** $210

R&D Time Range: 2-5 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	70	70	70	–	–	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines Plus Gas Engines

Relative Potential Benefit (overall rating): Low

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-10		0-10	0-20						–
Expected	5		5	10						–
Fraction of ECC Emissions Affected	0.12		0.46	.097						–
Noncombustion Controls Factor	.5		.8	.4						–
Relative Potential Benefit Factor	0.30		0.46	0.58						1.34

Implementation Time, years: 4-10 **most likely:** 8 **Relative Implementation Cost:** Low

Relative Priority Rating: D

R&D Opportunity: VII-6 Related to: VII-4; VIII-6, 10, 11, 12; VII-a, p, q, tt

Experimental Research on the Formation of Particulate and PNA Emissions From Gasoline Engines

Technical Objective and Approach

The objectives are to further characterize particulate and PNA emissions from gasoline engines, to gain an understanding of the mechanism by which they form during the combustion process, and to determine the relationship of these emissions to fuel composition and oil consumption and composition.

The approach should include basic studies and both single-cylinder- and multicylinder-engine studies.

Rationale and Incentive

The effect of the combustion process on PNA and particulate matter formation is only partly understood. Further study might result in the reduction of these pollutants through combustion-process modifications, fuel and lubricant changes, or oil-control improvements.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$1,000 **Recommended 5-year Funding, 1000's:** $1,000
R&D Time Range: 3-5 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	200	200	200	200	–

Evaluation

Sources Affected: Mobile and Stationary Gasoline Engines
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-50			0-60			0-10			–
Expected	22			23			5			–
Fraction of ECC Emissions Affected	0.12			.097			0.70			–
Noncombustion Controls Factor	0.5			0.4			0.8			–
Relative Potential Benefit Factor	1.32			1.34			0.70			3.36

Implementation Time, years: 4-10 **most likely:** 8 **Relative Implementation Cost:** Medium

Relative Priority Rating: D

R&D Opportunity: VII-7 **Related to:** VIII-17, 18; VII-bbb, ccc

Initiate Development of a Model of the Diesel-Engine Combustion Process by Analytical and Experimental Development of a Fuel-Air Mixing-and-Vaporization Model

Technical Objective and Approach

The short-range objective is to develop an analytically based understanding of the fuel-air mixing and vaporization phenomena that precede combustion in the diesel-engine cylinder. This would enable prediction of temperature-pressure-fuel concentration histories as a function of location in the combustion chamber up to the point at which combustion is initiated.

The approach should be a theoretical investigation supplemented by extensive experimental studies both in engines and in other types of laboratory combustion apparatus.

Rationale and Incentive

So far, investigators generally have been unable to qualitatively describe the diesel-engine combustion process in terms of local temperatures, fuel concentrations, reaction rates, etc. (although a good empirical understanding of ignition delay and overall rate of heat release exists). Development of a good model of the combustion process (including both physical and chemical factors) will provide knowledge of the mechanisms whereby pollutants are formed with current diesel combustion systems and may give significant insights into combustion process modifications that will reduce the pollutants. A first step toward formulating a good model of the combustion process is to develop a good mixing and vaporization model.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$1,000

Recommended 5-year Funding, 1000's: $1,000

R&D Time Range: 5 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	200	200	200	200	–

Evaluation

Sources Affected: Mobile and Stationary Diesel Engines

Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-90	0-50	0-90	0-60	0-90	0-75				–
Expected	48	25	48	23	48	39				–
Fraction of ECC Emissions Affected	0.11	.0074	.066	0	0.46	.042				–
Noncombustion Controls Factor	.5	.5	.5	.4	.5	.1				–
Relative Potential Benefit Factor	2.64	0.09	1.58	0	11.04	1.47				16.82

Implementation Time, years: 4-10 most likely: 6

Relative Implementation Cost: Medium

Relative Priority Rating: B

R&D Opportunity: VII-8

Related to: VII-9; VIII-6, 7; VII-w, xx, ddd, eee, jjj

Experimental Investigation to Identify Odor-Producing Constituents in Diesel-Engine Exhaust, the Mechanism of their Formation, and Combustion Modifications to Reduce Emissions of these Constituents

Technical Objective and Approach

The objective of this research is to identify the chemical species present in diesel-engine exhaust that contribute to its characteristic odor, to determine the mechanism of their formation, and to reduce emission of these species by combustion modification.

Several approaches exist for relating the chemical composition of diesel-engine exhaust samples to the odor of the exhaust. The chemical aspect can involve either analytical identification of compounds existing in diesel exhaust or preparation of synthetic exhaust gases for comparison on the basis of odor with diesel exhaust. All approaches should involve human panels for odor evaluation.

Following identification of the odor-producing compounds, the mechanism by which these compounds form should be investigated, primarily in laboratory combustion rigs.

Specific approaches to combustion modification cannot be determined until the odor-producing constituents and their mechanism of formation are identified.

Rationale and Incentive

One route to the reduction of odor-producing exhaust from diesel engines is to begin with the identification of the odorous compounds. If the odor-producing compounds can be identified, the mechanism of their formation can be identified using existing basic knowledge of the combustion process, provided a good mixing and vaporization model exists. Finally, a precise knowledge of the mechanism by which the odor-producing compounds form can lead to defining a combustion-process modification that will reduce odor emission.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$1,000
R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $500

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	100	100	100	100	100	–

Evaluation

Sources Affected: Mobile and Stationary Diesel Engines
Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range			0-90		0-90					–
Expected			48		48					–
Fraction of ECC Emissions Affected			.066		0.46					–
Noncombustion Controls Factor			.5		.5					–
Relative Potential Benefit Factor			1.58		11.04					12.62

Implementation Time, years: 4-10 **most likely:** 6

Relative Implementation Cost: Medium

Relative Priority Rating: B

R&D Opportunity: VII-9 Related to: VIII-4, 6, 8, 9, 10; VII-hhh, iii

Experimental Laboratory Research on Preflame and Nonflame Reactions in Diesel-Engine Combustion

Technical Objective and Approach

The objective is to obtain basic information on formation of smoke and odor-producing compounds in preflame and nonflame zones during diesel-engine combustion.

The approach should include basic chemistry studies of carbon formation during pyrolysis and subsequent flame combustion in fuel-rich regions, and of the production of odor-producing compounds by non-flame reactions in very lean regions. These studies should be conducted as laboratory research – not in an engine. In addition to establishing fuel-air distribution requirements, this research might suggest other modifications to the combustion process for reducing emissions.

Rationale and Incentive

Laboratory (nonengine) research on the preflame and nonflame reactions characteristic of diesel-engine combustion can help establish limits on the range of fuel-air ratios that can be permitted in local regions without producing odor and smoke. This research will assist in establishing goals for the degree of uniform fuel-air distribution that must be achieved to avoid excess emissions from diesel engines.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$350 Recommended 5-year Funding, 1000's: $350
R&D Time Range: 3-5 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	70	70	70	70	70	–

Evaluation

Sources Affected: Mobile and Stationary Diesel Engines
Relative Potential Benefit (overall rating): Medium High

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range	0-90		0-90		0-90					–
Expected	48		48		48					–
Fraction of ECC Emissions Affected	0.11		.066		0.46					–
Noncombustion Controls Factor	.5		.5		.5					–
Relative Potential Benefit Factor	2.64		1.58		11.04					15.26

Implementation Time, years: 4-10 most likely: 6 Relative Implementation Cost: Medium

Relative Priority Rating: B

R&D Opportunity: VII-10

Related to: VIII-3; VII-u, v, w, pp, aaa

Investigation of Kinetics of NO_x Formation in IC Engines With Fuel-Rich Mixtures

Technical Objective and Approach

The objective of this research is to investigate the possibility of reducing NO_x emission from IC engines by combustion-process or engine-hardware modifications which take advantage of new information to be generated in a study of the nitrogen-oxygen kinetics coupled with the hydrocarbon-oxygen combustion process. (This does not include implementation of existing knowledge of nitrogen-oxygen kinetics.)

The approach is to determine, by sampling or other procedures, the NO_x concentrations existing at discrete times and places within an engine operating at other than very fuel-lean conditions. The resulting data should be examined and correlated with engine operating variables to identify conditions which could be exploited to minimize the formation or to maximize the destruction of NO_x. The possibility of exploiting these conditions in a practical commercial engine would be examined.

Rationale and Incentive

The general behavior of the nitrogen-oxygen system is understood and this understanding can be applied to combustion processes which are sufficiently fuel-lean. However, the behavior is not understood when significant competition for O atoms occurs, for example, under fuel-rich conditions. Hence, the possibility exists that engine operating conditions could be found which exploit the (largely unknown) behavior of the nitrogen-oxygen system under these non-lean combustion conditions to reduce NO_x emissions. As NO_x from IC engines may be difficult to control otherwise, an increase in HC and CO emissions, which could be controlled downstream, might be acceptable.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $0-$400
R&D Time Range: 0-4 years

Recommended 5-year Funding, 1000's: $200

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	100	–	–	–	–

Evaluation

Sources Affected: All IC Engines
Relative Potential Benefit (overall rating): Medium

Pollutants Affected	CP	CO	HC	PNA	Odor	NO_x	Lead	SO_x	Ash	Σ
% Reduction, Range										
Expected						0-30				–
Fraction of ECC Emissions Affected						12				–
Noncombustion Controls Factor						0.42				–
Relative Potential Benefit Factor						.2				–
						4.03				4.03

Implementation Time, years: 4-10 most likely: 6

Relative Implementation Cost: Medium

Relative Priority Rating: D

R&D Opportunity: VII-New Concepts

Provision for Exploring New Concepts and New R&D Opportunities that Evolve from the Program, Accelerating Promising R&D, or Conducting Demonstrations of Promising Concepts for Reducing Emissions from Reciprocating Internal-Combustion Engines by Combustion Modification

Technical Objective and Approach

The objective is to provide for long-range flexibility in the R&D program to enable APCO to take advantage of opportunities that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the R&D program to explore the feasibility of new and novel concepts and to accelerate research, development, and demonstration of promising concepts for reducing emissions by combustion-process modification. Worthwhile ideas for combustion-process modification to reduce emissions from reciprocating IC engines might originate as the result of novel design concepts or through in-depth understanding derived from well-planned R&D. The merits of specific R&D opportunities should be decided by evaluating the particular concepts as they evolve.

Rationale and Incentive

Appropriate R&D support can be expected to encourage conception of IC-engine combustion-process modifications that might result in substantial emission reductions.

Gasoline Engines. Combustion-process modification appears to be the only engine modification route to achieving ultimate emission goals. Investigations of this kind are being conducted presently on exhaust-gas recirculation (EGR) and on stratified-charge engines. EGR modifies the combustion process by the introduction of an additional dilutent to the reactants. In a stratified-charge engine, the modification of the combustion process is more drastic and can result in the elimination of wall-quench effects.

Diesel Engines. The combustion process in diesel engines is characterized by compression ignition, operation with lean fuel-air ratios, the use of heavy hydrocarbon fuels with short ignition-delay properties, and some means of injecting the fuel into the cylinder at a controlled time and rate. Variations in these factors, particularly the way in which fuel is injected, strongly affect the combustion process and the resulting emissions. For example, there are several approaches to the fuel-injection process (e.g., direct-injection engines vs. precombustion engines) and their emission characteristics are substantially different in some respects.

Fuels. While there are candidate fuels, such as hydrogen, that could give low emissions, none are presently practical for various reasons including high cost, inadequate supply, engine derating, and problems in handling and on-vehicle storage. Although it appears at this time that there is no readily available suitable alternative fuel, there is no proof that such a fuel could never be found.

Recommended Funding Allocation

	'71	'72	'73	'74	'75	
Funding by Fiscal Year, $1000's	–	250	300	300	350	5-year Funding, 1000's: $1,200

Evaluation

This R&D Opportunity is unranked. Potential benefit, implementation time, implementation cost, and funding level for each specific opportunity must be evaluated when the opportunity is identified. The suggested funding level anticipates effort on several R&D opportunities.

Relative Priority Rating: N

TABLE VII-5. SUMMARY BY PRIORITIES

RECIPROCATING INTERNAL-COMBUSTION ENGINES

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
A	VII-1 Support of Development and Evaluation of **Stratified-Charge** Gasoline Engines	X	400	400	400	–	–	1,200	–
A	VII-2 Development of Implementation Criteria for **Lean-Mixture Operation of Gasoline Engines**	X	200	260	200	–	–	660	–
A	VII-3 Experimental Research on the Effect of **Fuel-Air Mixture Preparation** on Gasoline-Engine Emissions	X	100	100	100	–	–	300	
	Totals, Priority A		700	760	700			2,160	
B	VII-7 Initiate Development of a **Model of the Diesel-Engine Combustion Process** by Analytical and Experimental Development of a **Fuel-Air Mixing-and-Vaporization Model**	X	200	200	200	200	200	1,000	–
B	VII-8 Experimental Investigation to **Identify Odor-Producing Constituents in Diesel-Engine Exhaust**, the **Mechanism of their Formation** and Combustion Modifications to Reduce Emissions of the Constituents	X	100	100	100	100	100	500	–
B	VII-9 Experimental Laboratory Research on **Pre-Flame and Non-Flame Reactions** in Diesel-Engine Combustion	–	70	70	70	70	70	350	–
	Totals, Priority B		370	370	370	370	370	1,850	
C	VII-4 Analytical and Experimental Research on **Gasoline-Engine Wall-Quench Phenomena**	–	100	100	100	–	–	300	–

TABLE VII-5. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
D	VII-5	Experimental Research on the **Effect of Lubricating Oil** on Gasoline-Engines Emissions	–	70	70	70	–	–	210	–
D	VII-6	Experimental Research on the **Formation of Particulate and PNA** Emissions from Gasoline Engines	X	200	200	200	200	200	1,000	–
D	VII-10	Investigation of **Kinetics of Nitrogen-Oxide Formation** in IC engines **with Fuel-Rich Mixtures**	X	100	100	–	–	–	200	–
		Totals, Priority D		370	370	270	200	200	1,410	
N	VII-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Reciprocating Internal-Combustion Engines by Combustion Modification	–	–	250	300	300	350	1,200	–
		Totals, All Priorities		**1,540**	**1,850**	**1,740**	**870**	**920**	**6,920**	

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Chapter VIII

FUNDAMENTAL AND BROADLY APPLICABLE COMBUSTION RESEARCH

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CHAPTER VIII

FUNDAMENTAL AND BROADLY APPLICABLE COMBUSTION RESEARCH

SCOPE OF CHAPTER AND BACKGROUND

This chapter is concerned with combustion research that is fundamentally oriented and/or broadly applicable to the applied areas discussed in previous chapters. The term "fundamentally oriented" is used to indicate that the research is oriented towards gaining an understanding of, or gathering data about, combustion processes, rather than oriented primarily to solving specific problems in the applied areas. However, emphasis is placed not on obtaining scientific knowledge for its own sake, but rather on obtaining pertinent information that is potentially useful for reducing pollutant emissions from energy-conversion-combustion sources.* Further, the depth of the understanding being sought is generally restricted to that needed for engineering applications. Therefore, much of the research discussed in this chapter is empirical or phenomenological in character.

When the combustion process is viewed on an input-output basis, it is clearly a chemical process. Certain chemical species enter the process, and different chemical species emerge. However, any detailed examination of the combustion process reveals that the chemical process involved differs from many others in that by far the larger part of the chemical reactions occur, at least in homogeneous-gas reactions, in a very narrow zone – the combustion wave.

This characteristic of the combustion reaction, that it occurs in a narrow region essentially as a discontinuity, results from the highly exothermic character of the overall chemical reaction coupled with the moderately high activation energy of the overall reaction. Studies of the combustion process show that the process by which the discontinuity (or combustion wave, or flame front) propagates itself is dependent on heat and mass diffusion. Consequently, many of the easily observable characteristics of a flame are dependent on physical rather than chemical processes. Combustion in the commercially important heterogeneous systems (i.e., not premixed on a molecular scale) is even more dependent on physical factors, as mixing phenomena appear invariably to control the observed reaction rate.

Because of the observed importance of physical, largely aerodynamic, phenomena in practical combustion systems, combustion research has historically been in large part a branch of aerodynamics, particularly when the research has been related to engineering design problems.

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*A continuing problem encountered in discussing combustion research in the context of this study is that of separating combustion research, in the general sense, from combustion research directed towards the reduction of air-pollutant emissions. This separation proves to be difficult, as the areas overlap to a large extent with varying degrees of emphasis. Insofar as possible, a separation has been made. However, large areas remain in which the primary emphasis would ordinarily be assigned to "combustion research" rather than "pollution research"; yet these areas appear to require study if the objective of understanding the formation and fate of pollutant emissions from combustion processes is to be reached.

In this view, the details of the mechanism by which the fuel is oxidized and the heat of combustion is released are considered unimportant and largely ignored. However, as the concern of the equipment designer, and consequently of the combustion research investigator, has broadened to include air-pollution aspects, this situation seems to be changing. It may still be acceptable in this view to ignore the part chemistry plays in the main heat-releasing reaction. However, the role of chemistry, as contrasted to physics, in determining the emission of very low concentrations (in terms of the heat balance) of species other than CO_2, H_2O and N_2, probably cannot be ignored.

Figure VIII-1 illustrates one way in which the physical and chemical phenomena involved in combustion can be organized. The organization there shown can be regarded as a hierarchy ranging from very basic science at the bottom to applied engineering at the top.

Also illustrated in Figure VIII-1 are the approximate boundaries of research considered appropriate to the scope of this study. These boundaries were chosen on the assumption that the ultimate level of understanding required is roughly that sufficient to predict the emissions of pollutants from combustion processes. It is not intended that these predictions necessarily be made from "first principles". Predictions based on empirical and phenomenological models are perfectly acceptable as long as the predictions have useful accuracy and their limitations are known.

The following discussion is divided between **combustion physics** and **combustion chemistry**. This separation reflects the history of combustion research. However, a more unified approach would be desirable and will probably be developed in the future.

COMBUSTION PHYSICS

It is clear that fundamental studies of combustion physics cut across the classifications of combustion-equipment applications or source categories used in the Plan and discussed previously. The fundamental studies considered here are concerned more with equipment that simulates, or can be used to simulate, various flow paths through combustion devices than with actual practical devices. This type of approach can be especially important in the case of pollution-related combustion research, because in many combustion devices the significant pollution problems result from a small number of specific "bad" paths of flow through the devices. Recent progress in eliminating smoke emission from aircraft gas turbines emphasizes this point.

To approach the presentation of this type of path study in systematic manner, the phenomena involved in various combustion devices are classified into four different flame types and three time-history cases. This makes possible systematic consideration of pollution resulting from paths with various histories of temperature, composition, and so forth, as a function of time. First a brief description of the flame type is presented, then the manner in which it is related to air pollution is outlined, and finally various specific types of research programs which could give information necessary to fill in gaps in knowledge related to the prediction or suppression of air pollution are discussed. At the conclusion of this chapter the suggestions for experimental projects are presented as research opportunities.

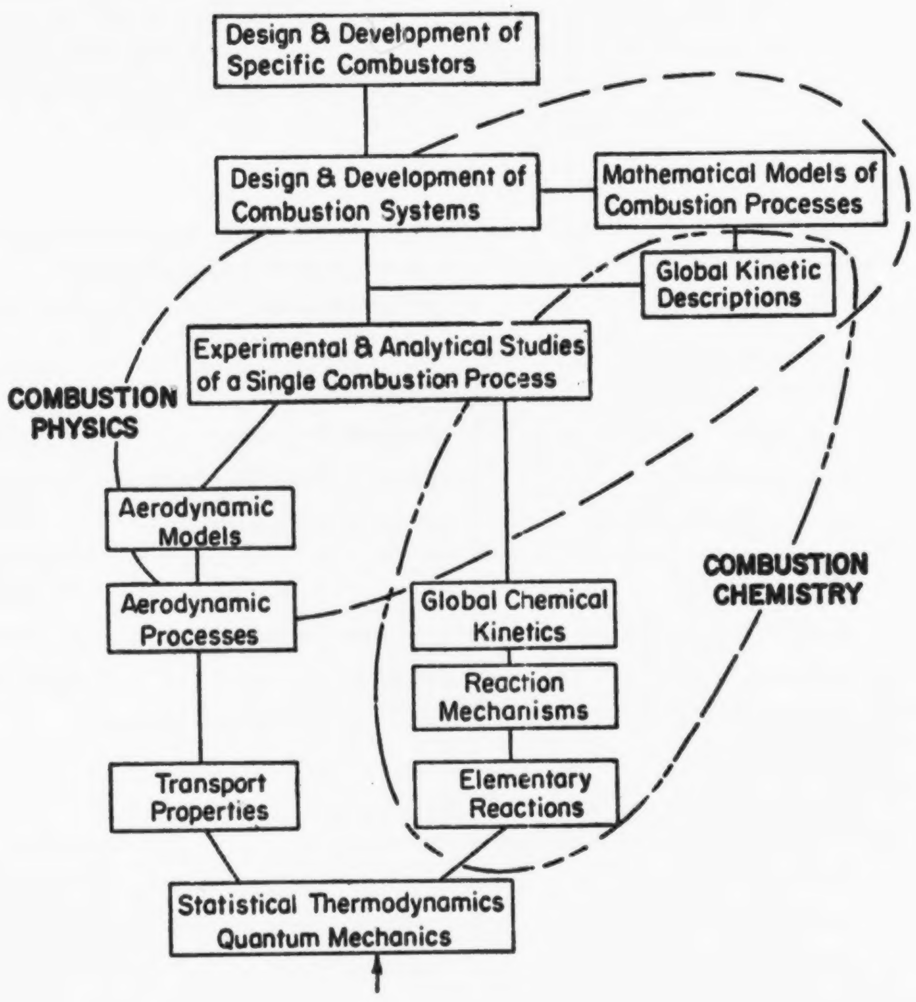
Design & Development of Specific Combustors
Design & Development of Combustion Systems
Mathematical Models of Combustion Processes
Global Kinetic Descriptions
Experimental & Analytical Studies of a Single Combustion Process
COMBUSTION PHYSICS
Aerodynamic Models
Aerodynamic Processes
Global Chemical Kinetics
Reaction Mechanisms
Elementary Reactions
COMBUSTION CHEMISTRY
Transport Properties
Statistical Thermodynamics Quantum Mechanics

Figure VIII-1. Hierarchies in Combustion R&D

CLASSIFICATION OF COMBUSTION PROCESSES

In general, the physical factors that influence the combustion process need to be understood to permit the prediction of pollutant output by a given combustor system under a given set of operating conditions. These factors include fuel properties and fuel preparation, mixing and turbulence, temperature, residence time, and dilution and recirculation. However, the degree to which each of these factors is important to any particular combustor is influenced by the general type of flame present and the general method in which the combustor operates. Therefore, in identifying specific items of research that should be carried out, it is helpful to classify the types of flame and combustion processes as shown in Table VIII-1. The importance of the various influences can then be judged as they bear on each type of flame and combustion process.

Table VIII-1. Classification Matrix of Combustion-Process Applications

Flame Type and Fuel	Continuous Cases	Transient Cases	Cyclic Cases
Premixed Gas	Industrial Processing	Industrial Processing	SI Engines
	Comm. & Residential Heating	Comm. & Residential Heating	Pulse Combustors
	External-Comb. Engines	External-Comb. Engines	–
Diffusion Gas	Central Stations	–	SI Engines
	Industrial Steam Generation	Industrial Steam Generation	CI Engines
	Industrial Processing	Industrial Processing	Pulse Combustors
	Comm. & Residential Heating	Comm. & Residential Heating	–
	Gas Turbines	Gas Turbines	–
	External-Comb. Engines	External-Comb. Engines	–
Droplet	Central Stations	–	SI Engines
	Industrial Steam Generation	Industrial Steam Generation	CI Engines
	Industrial Processing	Industrial Processing	Pulse Combustors
	Comm. & Residential Heating	Comm. & Residential Heating	–
	Gas Turbines	Gas Turbines	–
	External-Comb. Engines	External-Comb. Engines	–
Solid fuel	Central Stations	–	Pulse Combustors
	Industrial Steam Generation	–	–
	Industrial Processing	Industrial Processing	–
	Comm. & Residential Heating	Comm. & Residential Heating	–

In this matrix, the various combustion devices considered specifically in the preceding chapters are identified. While these two methods of classification (namely, by flame type and by application) are related, they are not identical. The purpose in using the flame classification here is to simplify the identification of fundamental work that can apply to one or more of the classifications used elsewhere in this report.

In using Table VIII-1, it should be noted that continuous combustion processes include steady-state operation at both maximum-load conditions, or design-load conditions, and part-load conditions.

Transient conditions include the changes from one load to another that cannot be treated as a series of quasi-steady-state conditions. Transient cases may be important when the changes are rapid compared with flow time through the system or with the time needed to achieve near-equilibrium environmental conditions. Start-up and shutdown are particularly severe cases, and they have received little attention as far as air pollution is concerned.

The cyclic process includes both the internal-combustion engine and potential pulse-combustor systems; part-load and transient cases in these systems are considered as included therein.

Four different flame types have been called out as of practical interest, namely, (1) premixed gaseous flames, (2) gaseous diffusion flames, (3) droplet flames, and (4) solid-fuel flames. The following sections cover, for each flame type, the information that is presently available or can be deduced, what is still required, whether it is reasonable to expect it to be obtained in the required time period, and the research that must be initiated to obtain the necessary information. Premixed flames are discussed first because many of the results obtainable from studies of premixed flames should be broadly applicable to the other three flame types.

Premixed-Gas-Flame Combustion

The premixed gas flame is the simplest of the four flame types shown in Table VIII-1. The atomic composition throughout the combustor is close to uniform, although preferential diffusion effects may cause deviations from uniformity.

Continuous Case. For the continuous-flow process, the major problem is predicting velocity and temperature patterns. Detailed methods for predicting the flame shape and the temperature patterns in combustion systems are not well developed, although a variety of semiempirical formulations are available. However, flow patterns in cold-flow systems are usually quite similar to those in combustion systems, so that modeling procedures and simple computational techniques can often be used to predict gross flow patterns.

From the viewpoint of air-pollution research, values of the pertinent flow and temperature parameters in a given combustor could be measured rather than computed. The measured parameters could then be related to the measured pollution concentrations. For two-dimensional (or axially symmetric) systems*, the ability to compute flow patterns by digital means is sufficient(1), providing reasonable assumptions can be made relative to the flame interface.

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*Many combustors can be mathematically simplified to two-dimensional (or axially symmetric) systems.

Transient Case. The remarks made previously concerning the continuous-flame case generally hold in the case of the premixed transient flame as well. Even the computational procedure mentioned can be extended to the transient case (at a greatly increased computational cost, however).

Cyclic Case. In the case of cyclic combustors, such as some SI engines and pulse combustors, the ability to determine temperatures, compositions, and velocities is not adequate. In the case of the SI engine, one wall of the combustion chamber is moving, the pressure and temperature are going through large ranges during a cycle, and the flame expansion rate is complicated by the fact that even the fundamental burning velocity of the fuel-air mixture can be varying throughout the cycle. The flow pattern is not expected to be symmetric, and the development of simple computational procedures to handle this cyclic problem cannot be expected in the near future.

In general, it is probable that the most profitable research relative to the pollution aspects of cyclic combustion physics will be hardware-oriented applied R&D. However, there is one area in which basic research on the production of pollutants should be carried out, and that is in regard to wall quenching. This can be investigated by bomb methods, although a close tie-in of available results with data on critical flash-back distance and related parameters indicates the possibility of profitably using continuous flow rigs in such a study.

The chance that a premixed pulse combustor will be of commercial significance in the near future is not large enough to warrant consideration here.

Gaseous Diffusion-Flame Combustion

The second flame type shown in Table VIII-1, the gaseous diffusion flame, is of interest not only in itself but because it forms a model for certain aspects of droplet combustion and solid-fuel combustion as well.

The mixing of fuel and air in the combustion region is an essential part of the diffusion-flame phenomenon and it is associated with pollutant production. As compared with the premixed-flame type, this mixing process introduces new experimental and theoretical complications. On the other hand, the mixing process is usually the gross rate-controlling factor in a turbulent diffusion flame. Consequently, the conditions of mixing are often of far more importance than chemical kinetic considerations for an understanding of such flames (possibly excluding some pollution aspects).

Continuous Case. Four different types of continuous diffusion flames can be distinguished: (1) the confined nonturbulent flame, (2) the unconfined nonturbulent flame, (3) the confined turbulent flame, and (4) the unconfined turbulent flame. In the confined flame, both fuel and air are in limited supply; in the unconfined flame, only the fuel is limited. Also, in the unconfined flame, buoyancy effects may play an important role in the observed phenomena by controlling the rate of air mixing into the flame. Generally speaking, simple theory will predict many of the gross details of steady-state gaseous diffusion flames, although some diffusion flames burn with a certain periodicity that is not fully understood. However, in the detail needed for pollution studies, the state of knowledge is not as advanced.

In discussions of turbulent diffusion flames, turbulent mixing is usually viewed as the rate-controlling factor; the reaction rate is not considered to be controlling, or even important, other than through its effect on flame stability. However, turbulence itself is not well understood in complex systems, and additional complications arise from the presence of a flame that adds a random set of volume sources as the gases expand by heat from random pockets of combustion.

Nonturbulent and turbulent diffusion flames do have a feature in common: the flames must be held at some point, line, or area. In a nonturbulent flame, the adjacent fuel and air interdiffuse over the edge of the burner. At some distance less than the quenching distance, a combustible mixture of varying composition is reached over a region greater than the normal flame thickness. In this region, at the quenching distance, a premixed flame develops and holds (or "seats") the diffusion flame. In fact, the diffusion flame may be pictured as a stepwise series of premixed flames, each with hotter but more dilute initial compositions.*

In a turbulent flame, this seating of the flame often does not occur. On the contrary, there are only local regions where the maximum turbulent flame speed can exceed the velocity of the on-coming fuel-air mixture. Therefore, the flame-holding points shift about in space as the local, low-velocity regions shift about in the turbulent stream. Furthermore, all of the leading edges of the flame must move at maximum premixed flame speed through the turbulent mixture, stretching and spreading the flame. When the flame no longer contacts enough local regions where it can "buck" the oncoming stream and not be extinguished, it will blow off unless held by some independent energy source. It is rather surprising that little quantitative information on this phenomenon in industrial-size confined burners is available in the literature.

It is clear that various local cells of the fuel and air will be of different compositions and temperatures, and that they will have different molecular and thermal dilutions as they approach the reaction zone. This variation from the average of local time and space concentrations is known as the *unmixedness* of the fluid.(2) Conditions will be extremely conducive to the production of various pollutants in some cells, while in others they will not. Thus, it might be expected that fluid-supply pattern, intensity and scale of turbulence, and local heat-sink conditions will have substantial effects on the production of pollutants.

In the above discussion, it has been shown that many features of diffusion flames are similar to those of premixed flames and that the character of the turbulence is a controlling factor in the performance of diffusion flames of high gross volumetric intensity. It is difficult to see how more than a gross understanding of the production of a pollutant in a turbulent diffusion flame would be possible without a fundamental understanding of the flame propagation in such a combustion system.

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*In many combustors, a premixed flame with insufficient primary air for complete combustion is followed by a diffusion flame to complete combustion; thus, there is an interrelationship between the two types of flames.

Transient and Cyclic Cases. Many of the cyclic and transient aspects of turbulent diffusion flames can be considered as large-scale turbulence effects similar to those discussed above.

Droplet and Particle Combustion

Droplet combustion in liquid-fuel-fired systems adds the additional complications of fuel injection (involving atomization), fuel trajectory, and fuel vaporization to the factors discussed thus far.

Atomization. Liquid fuel may be atomized for injection into the burner by a variety of methods. By far the most common methods are pressure-jet atomization and two-fluid atomization, ordinarily using either steam or air. As might be expected, there is a greater range of cases possible with two-fluid atomization with respect to type of fuel, size of droplet produced, and spray pattern. Literature is fairly extensive on the subject of atomization.(3) However, available information needs to be organized from the viewpoint of combustion applications to determine the extent of the practical gaps in knowledge.

Trajectory. For droplet combustion, the atomized fuel (and atomizing air or steam, if any) interacts in the combustion chamber with the surrounding atmosphere, aspirating the atmosphere into the spray. In turn, the incoming atmosphere causes separation of the fuel into finer or coarser droplets. Thus, droplet trajectories in the chamber are affected by the droplet directions and momenta at the time of breakup from the spray sheet, by the flow of the surrounding gas, and by their size and density. Effective atomizer and burner design can direct the large droplets to fuel-deficient regions. On the other hand, if the droplets are too large, they can impact on walls or go through the combustor without burning completely. The trajectory of a single droplet in a quiescent environment can be predicted; for the usual initial size and velocity of droplet, the droplet Reynold's number is sufficiently low to permit use of a simple viscous-drag law. In the event of evaporation and/or combustion, the Reynold's number effect seems to shift somewhat, but more important effects result from initial turbulence in the stream and droplets in close proximity acting as a coherent mass. However, these problems are being resolved through various research efforts.

Vaporization and Burning. As the droplets move into a hot gas environment, they begin to vaporize before they ignite.(4) In fact, a collection of sufficiently small droplets, uniformly distributed, can act as a premixed gaseous fuel. Larger droplets, on the other hand, will ignite and burn as individual droplets. The flame might burn as a sheath completely surrounding the droplet, or, if there is sufficient relative velocity, it might open at the leading edge and even pull away completely to the wake region. Again, close proximity of the droplets causes large interaction effects.

There can be other complications for commercial liquid fuels, as contrasted with the pure liquids on which vaporization and combustion tests are often made. While the lighter fractions are vaporized and burned, the heavier fractions can be pyrolyzing and polymerizing. Particulate matter (including cenospheres) can be formed and carried through the combustion system without burning. Such performance is undesirable from the standpoint of heat-exchanger fouling as well as from the air-pollution standpoint and attempts are usually made to avoid this condition. Less severe conditions might still lead to air-pollution problems while not producing the gross effects indicated.

Solid-Fuel Combustion. Fundamental studies of the burning of solid fuels can be restricted from the air-pollution standpoint, in the context of Table VIII-1, to include only the continuous-flow case. Only in the case of pulse combustors is there a problem with respect to cyclic combustion, and such solid-fuel combustors are of insignificant commercial importance at present. Transients in solid-fuel combustion are likely to be slow enough to be considered as a series of continuous-flow cases. Continuous-flow-combustion considerations can be divided between those relating to pulverized coal and those relating to the burning of considerably larger sizes of coal, either in a fixed bed or a fluidized bed.

Even with narrowing of the range of interest to continuous-flow combustion, the process seems to be considerably more complex than in the case of gaseous or liquid fuels. For instance, it is known that the rate of combustion, the fraction of early carbon burnout, and the nature of the solid residue depend strongly on the caking properties, volatility, and size distribution of the coal, and the inlet-air and furnace-wall temperatures – as well as the usual variables, including turbulence, that characterize the air stream.

Combustion of Pulverized-Coal. Despite the above-mentioned complicating factors, in many respects the combustion of pulverized coal resembles that of gaseous and liquid fuels. Since air is used to carry the pulverized coal into the combustion chamber, the injection process resembles some types of two-fluid liquid atomization, although the necessary "preatomization" of the coal precludes certain types of injection systems and makes some other possibilities more difficult. In the case of bituminous coal, after the pulverized fuel enters the combustion chamber there may be considerable gaseous fuel evolved as the particles are heated.

Combustion of a particle of pulverized coal usually occurs in two steps: (1) devolatilization and burning of the evolved gaseous matter and (2) burning of the remaining solid nucleus. Consequently, some results of studies of gaseous fuel flames from an air-pollution standpoint may be applicable here. The trajectories of solid particles follow laws similar to those governing liquid-fuel droplet trajectories. However, combustion is not in the gas phase as in the case of liquid fuel; it occurs on the solid surface.

The rate of combustion may be limited by diffusion rate at high temperatures or by chemical-reaction rate at lower temperatures. Furthermore, while most liquid-fuel droplets tend to become smaller with time (in a rather simple size-time relationship), solid-fuel particles may initially swell. Solid-fuel particles will also leave an ash residue.

Combustion in Fixed and Fluidized Beds. The problems of burning in fixed and fluidized beds of coal are of a specialized nature, and are quite different from the burning of pulverized coal; they are even less related to the liquid and gaseous-fuel combustion phenomena discussed previously. The comments made in Chapters III and V are considered sufficient for the purposes of this study.

SUGGESTED RESEARCH IN COMBUSTION PHYSICS

Discussed below are suggested types of research in combustion physics which could generate the information necessary to fill gaps in knowledge related to the prediction of, or suppression of, pollutant emissions from combustion processes. The organization follows the classification of combustion processes by flame type.

Premixed Flames

A series of fundamental studies on premixed flames can be identified that will yield immediate and practical results, although a complete explanation of the results will require a concomitant increased understanding of the chemical kinetics of the processes involved.

In these studies, a one-dimensional or plug-flow-type experimental combustor would be used. Temperature-rise time could be controlled by burner orifice size (in an array of orifices) and firing rate. Temperature-decay time could be controlled by surface-to-volume ratio, firing rate, and wall temperature.

With such a combustor, it would be possible to investigate recirculation (while varying gas temperatures* and point of admission of the recirculated gases), two-stage and multi-stage combustion, and air dilution** and leakage. In some cases, slight equipment modification might be required such as the installation of additional banks of injectors. Even the turbulence level could be controlled by insertion of turbulence-generating devices, although the possibility of catalytic surface reaction should not be overlooked.

With this idealized one-dimensional experimental condition, the effects of varying the temperature-time relation on various pollutants of interest can be studied for various fuel-air premix compositions. Specific studies should be made at the pertinent pressures and maximum temperatures of interest for methane, natural gas, ethane, ethylene, propane, butane, vaporized gasoline, and vaporized kerosene. Measurements should be made to determine emissions of particulates, HC, PNA, odor, and NO_x. In all cases, the N_2, O_2, CO_2, CO, temperature, and flow velocity should be measured.

Data obtained from these studies could form a basis for predicting emissions from more complex practical combustion devices. Possibly sufficient data would become available to enable testing of various hypotheses for handling kinetic data to obtain reasonably accurate predictions of pollutant levels.

To summarize the recommendations in regard to basic studies of the combustion physics of premixed flames, as they apply to air-pollution problems, the recommended work should be carried out principally with a plug-flow laboratory-type combustor. Some bomb studies or similar studies should also be made relative to quenching problems in IC engines. If there should be a large reduction or termination of funding by other Government and private sources that are currently supporting studies of laminar and turbulent flame speed and the flame stability of pertinent fuels at the conditions of interest (pressures, temperatures, and compositions), NAPCA support in these areas would also be important.

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*A separate combustor might be used to supply the "recirculated" gases.

**This approach might also be used at the proper pressure to study air-pollution effects of quenching of combustion in internal-combustion engines, as one example, and in gas-turbine combustors, as another example.

Gaseous Diffusion Flames

Basic studies of the combustion physics of gaseous diffusion flames, as they apply to air-pollution problems, should concentrate largely on combined experimental-analytical-theoretical investigations of the details of turbulent diffusion flames in the range of turbulence intensity and scale encountered in industrially significant combustors. In studies of the effects of various concentration gradients on pollution production, confined nonturbulent diffusion flames might also be used.

Droplet Combustion

Much of the necessary fundamental work on droplet combustion can be expected to proceed without any particular support from NAPCA. However, there are some areas in which additional support could accelerate significant programs and some areas which relate strictly to air pollution.

While there appears to be a considerable amount of information available on droplet production, trajectory, evaporation, and burning, there is a decided lack of up-to-date, unbiased, in-depth analysis. Adequate critical review of this information and publication of monographs not only would aid fundamental investigations in the field, by emphasizing the items needing clarification, but would aid development efforts in more applied areas of liquid-fuel combustion.

It would also appear worthwhile to make a fundamental study of the generation of pollutants by various fuels and various-size droplets moving through an environment comparable to that expected in practical combustors. It would be interesting for the design engineer to know, for instance, whether NO_x generation is promoted or discouraged by the burning of a fuel in a droplet sheath, as contrasted with the burning of completely vaporized droplets. Appropriate experiments should be carried out with the usual fuels and with droplets of the size range normally expected in a combustor.

Pulverized-Coal Combustion

It would appear that some research should be conducted on the combustion of the complex mixture of gases evolved when coal is heated rapidly. These are mostly complex hydrocarbons but they also include such simple gases as hydrogen and methane. The residual "coked" carbon particle, which will retain varying amounts of hydrocarbons (depending upon the original composition of the coal and the speed with which the particle is heated) should also be evaluated as a combustible particle.

In the case of pulverized coal itself, consideration should be given to the possibility that certain types of ash could have specific effects on the types of pollutants produced. Because both pyrolysis of the coal constituents and chemical reactions of chemically bonded nitrogen can take place during the coal-particle heating period, there is the possibility that particle-size distribution can affect pollutant production. The effect of such distributions on the various pollutants should be investigated. These investigations could be carried out in a plug-flow furnace such as described above for gaseous fuels.

Burning in Fixed and Fluidized Beds

The problems associated with burning in fixed and fluidized beds of coal are quite different from those associated with the burning of pulverized coal in conventional furnaces. However, fluidized-bed combustion occurs at a relatively low flow rate and with large sizes of coal elements; this means that a relatively simple type of fundamental experiment might be of value.

It is possible to visualize a simulated fluidized bed in which individual particles could be suspended in a hot gaseous medium of controlled composition and temperature. Their size, mass, and temperature history could then be studied. For the most part, however, efforts concerned with fundamentally oriented research in this particular area could be confined to abstracting pertinent information from the large amount of general literature on fixed and fluidized beds.

COMBUSTION CHEMISTRY

Combustion chemistry as related to pollutant emissions can be examined from two viewpoints: (1) the viewpoint of rigorous chemical kinetics and (2) the more-pragmatic alternative viewpoint in which any model, procedure, etc., which produces useful answers is acceptable.

RIGOROUS KINETICS

With respect to the first viewpoint, it might seem that the objectives of this section of the report should be to identify the information on chemical kinetics that is needed to understand the emission of pollutants from the combustion process and to recommend a program of research to fill such information gaps. While such an approach seems quite logical, it is not currently feasible. This is due largely to the fact that the probably relevant body of chemical information is staggering, and perhaps unmanageable, in size. Further, this body of information is largely undeveloped, and criteria for selecting the more technologically important parts of this body of information are largely unknown.

This does not mean that chemical kinetics can make no contribution to the understanding of pollutant emissions. In fact, such contributions have already been made, for example in providing understanding of the thermal fixation of nitrogen in fuel-lean combustion systems, understanding of the oxidation states in which sulfur appears in combustion gases, and understanding of the oxidation of CO in the CO - H_2 - O_2 system.

From the standpoint of chemical kinetics, a chemical reaction is "understood" if rate constants are available for all the elementary reactions involved in the process leading from reactants to products. An elementary reaction, for example

$$O + N_2 \longleftrightarrow NO + N \quad ,$$

is a reaction that occurs as shown by the equation without intermediate steps. For the high-temperature N_2 - O_2 reaction, three elementary reactions involving six chemical species appear to provide an adequate description of the system, although additional species and elementary reactions may be involved to some extent. In the case of the H_2 - O_2 system, perhaps nine chemical species are observed, and for the CH_4 - O_2 system, perhaps thirteen – without considering those species containing more than one carbon atom. The complexity of the situation where multicomponent commercial fuels, such as heavy oils, are involved can perhaps be imagined.

The possible elementary reactions between these species are not easy to study: in general, an individual elementary reaction cannot be isolated from the overall process and examined independently. The species involved are often highly reactive and fleeting.

The chemically reacting systems that should be considered in ordinary combustion studies, and in studies of the emission of pollutants, can probably be classified as follows:

- Nitrogen – Oxygen
- Hydrocarbon – Oxygen
- Hydrocarbon – Nitrogen
- Organically Bound N, P, S, Metals, etc. – Oxygen.

Some aspects of these systems and the present state of knowledge concerning them are discussed in the following sections.

The Nitrogen-Oxygen System

The nitrogen-oxygen system, compared with hydrocarbon-oxygen systems, is not complex. Yet a sizable number of elementary reactions can be written just for the species usually considered in flames. This system holds practical interest for some aerospace and industrial applications and it has some characteristics which make it attractive to the pure scientist as well. Consequently, it has been the subject of much study, and estimates of the rate constants for a great many of the possible reactions are available.(5,6)

If the equilibria of the N_2 - O_2 system are examined at the temperature levels found in flames, it appears that NO is the major product, the amount of NO_2 being much smaller. N_2O may be involved as an intermediate in the decomposition of NO. It is worth noting that, other factors being fixed, the NO + NO_2 concentration does not increase monotonically with temperature. A maximum appears in the region of 3500 K, after which the equilibrium amounts of NO + NO_2 diminish.(7)

Once formed, NO and NO_2 may react with O, H, OH, hydrocarbon radicals, etc., just as do many other species to be found in flames. Even in systems where these reactive substances are present, however, reasonable success has sometimes been achieved in describing the kinetic behavior of NO by using models which exclude many such reactions.(8) Thus, even in hydrocarbon-air systems, a reasonably satisfactory treatment of the NO problem has sometimes been achieved. Usually two relatively simple mechanisms are invoked. Above 1700 K or so,

$$O_2 + M \longleftrightarrow 2\,O + M$$

$$O + N_2 \longleftrightarrow NO + N$$

$$N + O_2 \longleftrightarrow NO + O \quad .$$

The first reaction is often assumed to be equilibrated, although the assumption is not essential and is sometimes quite wrong. There seems little reason to doubt the importance or essential correctness of this mechanism.

At intermediate temperatures (below about 1700 K) where few N atoms can exist (and therefore the previous mechanism becomes very slow), the elementary reaction,

$$N_2 + O_2 \longleftrightarrow 2NO \quad ,$$

has been used. Until fairly recently this was thought to be a simple homogeneous bimolecular reaction proceeding through a four-center-activated complex. However, recent evidence suggests that the intermediate temperature decomposition (the reverse reaction) proceeds with

$$2NO \longrightarrow N_2O + O$$

as a rate-determining step, probably followed by

$$N_2O \longleftrightarrow N_2 + O$$

$$2\,O + M \longleftrightarrow O_2 + M \quad .$$

If this is true, then a mechanism of formation of NO in the N_2 - O_2 system in this temperature range is not necessarily simply the "reverse" of the latter three equations. Therefore, the mechanism and rate of formation of NO in the nitrogen-oxygen system below about 1700 K are uncertain.(9)

At still lower temperatures – below perhaps 1100 K – heterogeneous reactions begin to predominate. This region is of little interest in combustion processes.

The two sets of high-temperature reactions provide a commonly used basis for reaction modeling. However, other elementary reaction rates are known for this system and they could be included in a model if desired.

It is perhaps possible to assert that NO formation rates can be kept small by keeping the temperature low and by keeping the amounts of O_2 and N_2 small. Further generalities are not warranted because multiple roles may be played by N_2 and O_2. Perhaps this can be better appreciated if it is noted that, beyond some point, N_2 or O_2 can function as a temperature-moderating diluent as well as a reactant. There is yet another possible role. Nitrogen may alter the thermal conductivity sufficiently in some situations to overcome the diluent role and make a flame hotter, not cooler.(10) Obviously these roles must be established in each instance.

The Hydrocarbon-Oxygen System

Complete combustion of a hydrocarbon is defined as a process in which the only reaction products are CO_2 and H_2O. Practical instances of hydrocarbon combustion yield a considerably more varied product list. These other carbon-containing species are attributed to incomplete combustion.

Hydrocarbon-oxygen systems are impressively complex. Below about 500 K, hydrocarbons may react slowly with oxygen. Between about 500 and 700 K is a region of complex ignition behavior often called the cool-flame region. These flames may be extinguished, stabilized, made periodic, or caused to ignite a second, hotter flame, depending on other variables. Products of such cool flames are various oxygen-containing species that are destroyed at higher temperatures. Cool flames may be related to preignition phenomena in internal-combustion engines. At present, it is considered likely that such reactions proceed by a chain process, and suggestions have been made for such mechanisms.(11)

High-temperature oxidation reactions of hydrocarbons are also enormously complex. It is usually thought that pyrolysis (cracking) must be considered in addition to reactions of oxygen and oxygenated species. Pyrolysis reactions are usually described in terms of Rice-Herzfeld mechanisms(12). [Considerable discussion has recently ensued about the importance of molecular mechanisms. The issue still seems undecided(13).] Rice-Herzfeld mechanisms involve the creation of free radicals (usually by fission of a reactant), chain propagation by hydrogen abstraction from the parent compound and/or radical stabilization by splitting off olefins, and termination by radical destruction. In the case of combustion, free radicals could be created by O, OH, or H attack on the hydrocarbon. Hydrocarbon radicals might then react in a number of ways. If the radical is massive, it might undergo fission to form an olefin and another less-massive radical.

In oxygen-deficient regions of a combustion process, radical concentrations may become sufficiently high for radical recombination and polymerization reactions to become significant. Sizable polymers may undergo molecular rearrangements, plus hydrogenation and dehydrogenation reactions, depending on local conditions. In this way it is possible to rationalize the persistence of hydrocarbons in quenched combustion gas from fuel-rich regions as due to radical recombination; polynuclear aromatics as due to polymerization plus hydrogenation favored at lower temperatures; and combustible particulates as due to polymerization, ring-forming rearrangements, and dehydrogenation favored at higher temperatures.

This, of course, does not begin to account quantitatively, or even completely qualitatively, for such processes. No attention has been paid here, for example, to nucleation, to different classes of combustible particulates that have been recognized, or to the effect of electric fields.

In fuel-lean regions it is usually considered that hydrocarbons will be fragmented by OH and O attack with the formation of CH_3, H_2O, and lower-molecular-weight hydrocarbons. CH_3 may react with O or O_2 ultimately to form CO. The CO is thought to be converted to CO_2 largely by reaction with OH.(14) The specific reaction rates for the reaction of hydrocarbons with OH are probably somewhat higher than for the reaction of CO with OH. Thus, until the hydrocarbon concentration is reduced, most OH will react with hydrocarbons rather than with CO, and the elimination of CO in combustion is ultimately tied to the completeness of hydrocarbon oxidation.

The Hydrocarbon-Nitrogen System

The hydrocarbon-nitrogen system includes all of the hydrocarbon pyrolysis reactions, and what has been stated about them previously applies here as well. There are two other relevant classes of reactions that belong in this system: the nitrogen-hydrogen and the nitrogen-atom-hydrocarbon reactions. Many of the rate constants in the nitrogen-hydrogen system have been estimated.(5) There is at least a basis for including the system in a model if this is desired. Nitrogen-atom-hydrocarbon reactions have been observed, although extensive detailed information does not seem to be available. However, at present more detailed knowledge of this reaction system is probably unimportant.

Organics (Containing Chemically Combined N, P, S, Metals, Etc.)-Oxygen System

It is probably necessary to consider such organics individually when quantitative results are of interest. However, two rather general statements might be made. First, if molecules containing P, S, metals, etc., are to be considered pollutants, no type of combustion modification alone can contribute to the solution of the emission problem. This is merely because the element will survive any chemical process. If it is considered objectionable, it will have to be removed from the input or the exhaust. Second, it is likely that the mechanisms and rates of the reactions of nitrogen contained in a fuel will depend on the details of its chemical environment in the fuel. It is not clear that mechanistic knowledge of such reactions will have an important bearing on near-term engineering design to control NO_x.

ALTERNATIVES TO RIGOROUS KINETICS

The approach of rigorous chemical kinetics would seem to be the preferred approach to problems in combustion chemistry in that such an approach promises the greatest generality of results. However, this approach does not appear to be currently feasible, at least for the totality of problems considered here. Thus some alternative approach is needed.

As in all cases where engineering demands exceed the capabilities of basic science, the alternatives have been empirical and phenomenological descriptions of the processes of interest. The major difficulty with such approaches is that there is no assurance that the description will have the generality required for practical application. This difficulty has been extensively discussed in terms of modeling and scale-up of chemical processes. However, useful results are possible, even though limited. Examples include global* reaction-rate models for heat release in hydrocarbon-air systems, empirical models correlating certain emissions from gasoline engines, and mixed models of the combustion process in rocket engines. Although phenomenological descriptions may be limited in generality, it can always be hoped that further study and refinements will extend their usefulness.

SUGGESTED RESEARCH IN COMBUSTION CHEMISTRY

Much of the research suggested in the preceding section on combustion physics could equally as well have been regarded as related to combustion chemistry, specifically the development of an empirical global-kinetic scheme relating the emission of pollutants to the (mainly) physical-process variables. The remaining research to be considered here is essentially of a finer cut: attempted isolation of specific features or parts of the combustion process which have a distinctly chemical nature.

Within the realm of combustion chemistry, the pollutants of greatest concern are those involving products of incomplete combustion, that is, products that are not fully oxidized, and nitrogen oxides.

The research activities suggested by the above considerations are:

- Information should be obtained on chemical kinetics of simplified systems and isolated parts of the combustion process where possible. Specifically, studies of the interactions of the N_2 - O_2 system and the CO - O_2 - H_2 system with some simplified HC - O_2 system seem indicated.

- Long-range basic chemical kinetic studies of the HC - O_2 - N_2 system and the development of schemes for dealing with complex reacting systems are needed.

- Empirical descriptions should be developed of the reaction kinetics involved in the formation and destruction of products of incomplete combustion and NO_x.

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*The term "global" is used here both in the sense of overall and in the sense that internal details are excluded.

SUMMARY OF CURRENT AND RELEVANT FUNDAMENTAL COMBUSTION RESEARCH

Before listing the ongoing fundamental research on air pollution as related to the combustion process, general sources of published information in this area should be noted. A significant portion of such work in the U.S. and abroad is eventually reported or referred to in the volumes containing the papers presented at the biannual International Symposia on Combustion, sponsored by The Combustion Institute. A second important collection of fundamental combustion papers is *Combustion and Flame,* the journal of The Combustion Institute. Centers of fundamental research in this area can easily be identified from these sources. Other papers are scattered through the technical literature.

As discussed elsewhere, a systematic search was made of the literature to identify currently active programs related to the combustion aspects of air pollution. The projects identified in this search were screened from the point of view of fundamental research. The projects of interest are listed in Table VIII-2 (Combustion Physics) and VIII-3 (Combustion Chemistry). In these projects, either the spirit of the study appears to be fundamental or the procedure and/or expected results will apparently fall in this area. Information on time, cost, and rate of effort was almost completely lacking; therefore, these items are not included in the tabulation.

RESEARCH OPPORTUNITIES RECOMMENDED FOR THE 5-YEAR PLAN

Opportunities for fundamentally oriented research activities in combustion were recommended in the following categories:

- Physical Orientation
    - Path-history relations
    - Single and small number of droplets and particulates
    - Combustion in fluidized beds
    - Turbulence and droplet monographs
- Chemical Orientation
    - PNA, soot
    - HC - O_2 kinetics
    - NO_x - HC kinetics
    - (Miscellaneous)
- Combined
    - Global kinetic descriptions

The 31 fundamental and broadly applicable research opportunities that were identified are described in more detail at the end of this chapter, following the description of the procedure used for priority ranking. Of the 31 research opportunities, 27 of these have been evaluated and priority ranked, one is unranked, and 3 are discussed but not recommended. A summary by priorities is provided at the end of this chapter.

Table VIII-2. Current Research in Combustion Physics

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-a	Low emission continuous flow combustion for vehicle propulsion systems	NAPCA-DMVRD CPA 22-69-128	Marquardt Co. Van Nuys, Cal.	C. V. Burkland	Develop all technical information necessary to optimize continuous-flow combustion systems in mobile equipment for lowest possible emissions	96,683 (FY '69)
VIII-b	Research and development engineering services	NAPCA-DPCE CPA 22-69-144 Task No. 4	Mass. Inst. of Tech. Cambridge, Mass.	E. R. Gilliland K. Smith	Collect and organize current theories, data, and empirical expressions regarding heat transfer in fluidized beds. Interpret, evaluate, and rework this information in an effort to develop an improved physical model, and/or a more effective empirical expression	14,786 (FY '69)
VIII-c	Liquid fuel injection and combustion	NAPCA-ORG AP 00906	Rutgers Univ. New Brunswick, N.J.	R. L. Peskin C. E. Polymeropoulos	Make experimental and analytical study of the basic mechanisms of ignition and combustion of single- and multi-drop configurations	28,068 (FY '70) 37,385 (FY '69)
VIII-d	Engine emission reduction by combustion control	NAPCA-ORG AP 00560	Penn. State Univ. Univ. Park, Pa.	W. E. Meyer S. S. Lestz	Determine effect on HC and CO emissions of homogeneous charge engines by heterogeneous flame propagation due to local variations in air motion	50,238 (FY '70) 52,262 (FY '69)
VIII-e	Reduction of atmospheric pollution by application of fluidized-bed combustion	NAPCA-DPCE	Argonne Nat. Lab. Argonne, Ill.	A. A. Jonke	Evaluate potential of fluidized-bed combustion for pollution control	190,000 (FY '69) 267,000 (FY '70)
VIII-f	Characteristics of flames causing pollution	NAPCA-DPCE	Bureau of Mines Explosives Res. Ctr. Pittsburgh, Pa.	J. Grumer M. E. Harris V. R. Rowe E. B. Cook	Study the factors that lead to or limit emissions of NO_x, CO, and light hydrocarbons in gas appliances and develop a burner design that utilizes these findings	201,000 (FY '64-67) 77,000 (FY '63) 25,000 (FY '69)
VIII-g	NO_x from coal combustion	NAPCA-DPCE	Bureau of Mines Pittsburgh, Pa.	D. Bienstock R. L. Amsler E. R. Lauer, Jr.	Evaluate the factors involved in NO_x formation during coal combustion	–
VIII-h	Ignition of heterogeneous and condensed phase systems by intense laser radiation	Bureau of Mines	Bureau of Mines Explosives Res. Ctr. Pittsburgh, Pa.	I. Liebman H. E. Perlee	Determine if there is a minimum particle size below which a radiantly heated particle will not self-ignite or ignite a flammable atmosphere	–
VIII-i	Yield of nitric oxide from constant volume combustion	NASA	UCLA Los Angeles, Calif.	R. D. Kopa	Determine the effect of wall properties on the yield of nitric oxide formed during combustion in a constant-volume reaction vessel	–

Table VIII-2. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-j	Complex mixing models for chemical reaction	U.S. Air Force Off. of Scientific Res.	City College Res. Found. New York, N.Y.	R. Shinnar	Evaluate the effect of the stochastic and nonuniform nature of the transport processes on non-isothermal nonlinear reactions. Special attention will be paid to the unsteady behavior of exothermic reactions in premixed and non-premixed flow systems	–
VIII-k	Nucleating agent injection mechanisms	U.S. Air Force	U.S. Air Force Cambridge Res. Labs Cambridge, Mass.	S. J. Birstein	Study experimentally the break-up of droplets injected into high-velocity gas streams	–
VIII-l	Investigation of conditions leading to spontaneous ignition	U.S. Air Force	Ohio State Univ. Res. Foundation Columbus, Ohio	R. Edse	Analytically and experimentally investigate the conditions leading to spontaneous ignition in flowing explosive gas mixtures	–
VIII-m	Wave dynamic studies	U.S. Air Force Off. Scientific Res.	Univ. of Calif. Berkeley, Calif.	A. K. Oppenheim	Investigate gas-wave-dynamic phenomena during transition from combustion initiation to establishment of stable detonation in reactive gaseous media	–
VIII-n	Compression-ignition engine combustion phenomena	U.S. Army Coating Chem. Lab.	Southwest Res. Inst. San Antonio, Tex.	R. D. Quillian, Jr.	Obtain a more basic insight into compression-ignition process and to investigate effects of fuel properties on engine performance and exhaust emissions	–
VIII-o	Analytical studies in burning initially unmixed reactions	U.S. Army	TRW, Inc. Redondo Beach, Calif.	F. E. Fendell	Make a theoretical study of the effect of free convection on thin flame shape, droplet drag, and surface mass transfer rates of a burning spherical droplet	–
VIII-p	Internal combustion engine simulation	U.S. Army Tank Auto. Command	Univ. of Wis. Madison, Wis.	P. Myers O. Uyhara	Make computer simulations of diesel and Otto cycle engines with correlation of exhaust smoke to various parameters	–
VIII-q	The study of flame propagation in clouds of solid fuel particles in air	Nat'l Sci. Found.	Worcester Polytech. Inst. Worcester, Mass.	C. W. Shipman	Study the propagation of flame in clouds of solid fuel dispersed in air by mapping the composition, density, and velocity throughout the burning zone, to deduce reaction rates from the appropriate material balance equations.	–
VIII-r	Chemically reacting flows	State of California	UCLA Los Angeles, Calif.	V. E. Denny A. F. Mills	Analyze (using numerical methods) turbulent reacting flows in ducts including effects of intra-particle heat and mass transfer in the catalytic conversion of air pollutants.	–

Table VIII-2. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-s	Investigation of transient diffusion flame phenomena in a diesel engine combustion chamber	Caterpillar Tractor Co.	Univ. of Ill. Urbana, Ill.	W. L. Hull E. K. Buchholz	Determine what happens in the combustion of chamber of a diesel engine under very highly supercharged conditions	–
VIII-t	Air pollution problems relating to combustion		Purdue Univ. Lafayette, Ind.	L. F. Albright	Determine surface and heat transfer effects on nitric oxide production in combustion gases	–
VIII-u	Desulphurizing combustion in a chemically active fluidized bed	Esso Petroleum Co., Ltd.	Esso Petroleum Co., Ltd. England	G. Moss J.W.T. Craig	Develop a fluidized bed to effect the reduction of sulfur oxides emissions from oil fuel combustion	–
VIII-v	Short term work on pollution from petrol engines	MIRA Research Programme	Motor Industry Res. Asso. Warwickshire, England	C. D. Haynes M. Southall	Assess use of exhaust recirculation as a means of controlling nitric oxide, to assess variable dilution sampling method	–
VIII-w	Long term work on pollution from petrol engines	MIRA Research Programme	Motor Industry Res. Asso. Warwickshire, England	A. E. Dedd Z. Holubecki I. D. Lytollis	Assess the effect of mixture quality and combustion chamber configuration on exhaust emission of a single cylinder engine	–
VIII-x	Combustion of monosized droplet streams in stationary self-supporting flames	Shell (Fellowship)	Sheffield Univ. England	A.S.M. Nuruzzaman	Determine the effect of fuel characteristics, drop size, and droplet spacing on the combustion rate of droplets	–
XIII-y	Research into flames and combustion with emphasis on the domestic and commercial utilization of gas	–	The Gas Council Watson House Res. Div. Fulham, London, England	E.A.K. Patrick	–	–
XIII-z	Studies on flame aerodynamics and operating variables to reduce emissions	–	Res. Center of the French (National) Coal Industries France	M. Delanney M. Busso	–	–

Table VIII-3. Current Research in Combustion Chemistry

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-aa	Infrared spectroscopic study of gas-solid interactions	NAPCA-DPCE CPA 22-69-59 CPA 70-63	General Technologies Corp.	J. S. Burton	Develop a rapid technique for providing quantitative information about the mechanism of a heterogeneous reaction	51,879 (FY '69) 39,643 (FY '70)
VIII-bb	Structures of some oxides of nitrogen	NAPCA-ORG AP 00018	Penn. State Univ. Univ. Park, Pa.	I. C. Hisatsune	Investigate the structures and reactions of some oxy-nitrogen compounds	19,016 (FY '70) 21,739 (FY '69)
VIII-cc	Microkinetics studies in reactions of nitric oxide	NAPCA-ORG AP 00265	Calif. Inst. of Tech. Pasadena, Calif.	W. H. Corcoran	Study reactions of oxides of nitrogen at room temperatures and in plasma jets of argon, to study the partial oxidation of hydrocarbons, particularly at very low concentrations of oxygen	None (FY '70) 575 (FY '69)
VIII-dd	Kinetics and thermochemistry	NAPCA-ORG AP 00353	Stanford Res. Inst. Menlo Park, Calif.	S. W. Benson		97,759 (FY '70) 95,584 (FY '69)
VIII-ee	Kinetic behavior of inorganic radicals	NAPCA-ORG AP 00391	Kansas State Univ. Manhattan, Kan.	D. W. Setser	Find ways of producing inorganic free radicals in clean sources so that rate constant can be measured in a direct way	41,502 (FY '70) 32,292 (FY '69)
VIII-ff	Reactions of SO_2 with hydrocarbon CO and H_2	NAPCA-ORG AP 00633	Cornell Univ. Ithaca, N.Y.	S. H. Bauer		54,716 (FY '70) 64,705 (FY '69)
VIII-gg	Matrix isolation of nitrogen oxides	NAPCA-ORG AP 00638	Howard Univ. Washington, D.C.	W. A. Guillory		3,500 (FY '70) 32,918 (FY '68)
VIII-hh	Activation energies for radical and molecular reactions	NAPCA-ORG AP 00698	Stanford Res. Inst. Menlo Park, Calif.	S. W. Benson		29,861 (FY '70) 30,501 (FY '69)
VIII-ii	Kinetics of sulfur-oxide formation in flames	NAPCA-ORG AP 00464	Battelle Mem. Inst. Columbus Lab. Columbus, Ohio	A. Levy	Determine kinetics and mechanism of sulfur oxidation using a mass-spectrometer	43,697 (FY '70) 49,876 (FY '69)
VIII-jj	Use of electric fields in combustion	NAFCA-ORG AP 00643	Penn. State Univ. Univ. Park, Pa.	R. J. Heinsohn	Study the production of carbon and nitrogen oxides in flames subjected to electrostatic fields	17,462 (FY '70) 32,804 (FY '69)
VIII-kk	Reduction of polycyclic aromatic hydrocarbons	NAPCA-ORG AP 00323	Univ. of Birmingham Birmingham, England	R. Long R. Perry M. D. Crittenden	Study pyrolysis in diffusion and formation of polycyclic aromatic hydrocarbons during incomplete combustion	7,675 (FY '70) 4,290 (FY '69)
VIII-ll	Kinetics of NO at high temperatures	NAPCA-ORG AP 00858	Drexel Inst. of Tech. Philadelphia, Pa.	R. A. Matula		35,916 (FY '70) 46,526 (FY '69)
VIII-mm	Kinetics of particle growth	NAPCA-ORG AP 00758	Clarkson College of Tech. Philadelphia, Pa.	F. C. Goodrich	Determine the rate of growth of aerosol particles experimentally and theoretically	17,772 (FY '70) 28,366 (FY '69)

Table VIII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-nn	Photolysis and fluorescence of oxides of nitrogen	NAPCA-ORG AP 00595	Ill. Inst. of Tech. Chicago, Ill.	H. Von Weyssenhoff	Measure fluorescence spectra and lifetimes of nitrogen dioxide with spectral resolution of both exciting and emitted light	None (FY '70) 24,416 (FY '69)
VIII-oo	Chemistry of sulfur in hot combustion gases	NAPCA-ORG AP 00639	Univ. of Washington Seattle, Washington	C. B. Meyer	–	56,007 (FY '70)
VIII-pp	Kinetics of NO and CO formation in combustion gases	NAPCA-ORG AP 01228	Mass. Inst. of Tech. Cambridge, Mass.	J. C. Keck	–	46,694 (FY '70)
VIII-qq	Diesel fuel combustion chemistry as related to odor	NAPCA-ORG AP 00576	Drexel Univ. Philadelphia, Pa.	R. A. Matula	–	29,863 (FY '70)
VIII-rr	Physical chemistry of high temperature gases	NASA	NASA Lewis Res. Ctr. Cleveland, Ohio	R. S. Brokaw	Obtain knowledge of the reaction rates and mechanisms in high temperature gases	–
VIII-ss	Gas reaction kinetics	U.S. Navy ONR	Harvard Univ. Cambridge, Mass.	G. Kistiakowsky	Identify first formed fragments and their electrical state by analysis of chemiluminescent spectrum from reactions of oxygen with simple hydrocarbons	–
VIII-tt	Ion-molecule reactions in flames	U.S. Air Force SREP	IIT Res. Inst. Chicago, Ill.	P. Feng	Study ion-molecule (including negative ions) reactions in flames using a mass spectrometer	–
VIII-uu	Kinetic spectroscopy of chemically active systems	U.S. Air Force Off. Scientific Res.	Indiana Univ. Bloomington, Ind.	E. J. Bair	Elucidate detailed quantitative mechanisms and rates of the individual chemical processes which contribute to overall results of complex reactions and to determine the distribution of energy in reaction systems and its rate of change	–
VIII-vv	Pyrolysis of metal and metal hydride particles	U.S. Air Force Off. Scientific Res.	Univ. Denver Denver, Colo.	W. H. McLain	Provide detailed experimental information concerning important chemical and physical processes associated with the pyrolysis and combustion of metal and metal hydride particles	–
VIII-ww	Sychroton photoionization with mass spectrometric detection	U.S. Air Force Off. Scientific Res.	Univ. of Wisc. Madison, Wisc.	J. W. Taylor	Study the ionization and decomposition of molecules and free radical species using radiation from a synchrotron	–

Table VIII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigation	Objective or Scope	Funding, $
VIII-xx	Turbulence in gaseous detonations	U.S. Air Force	General Elec. Schenectady, N.Y.	D. R. White	Determine by spectroscopic techniques the concentration of selected species of light hydrocarbons and oxygen in shock waves and examine the effect of selected additives as reaction promotors and inhibitors	–
VIII-yy	Kinetics of reactions in flames and detonations	U.S. Air Force	U.S. Air Force Aerospace Res. Lab. Dayton, Ohio	K. Scheller	Gain information on the mechanism and kinetics of reactions in flames, shock waves, and detonations	–
VIII-zz	Infrared chemiluminescence from gas reactions	U.S. Air Force	U.S. Air Force Cambridge Res. Labs. Cambridge, Mass.	A. T. Stair	Conduct controlled laboratory studies to determine the partition of energy into the internal modes, to perform theoretical studies to describe the temperatures and populations of equilibrium and nonequilibrium gases	–
VIII-aaa	Quantitative high temperature infrared spectroscopy	U.S. Air Force Off. Scientific Res.	Technion Res & Dev. Found. Haifa, Israel	U. P. Oppenheim	Determine the laws which govern the emission and absorption of CO_2, H_2O, NO, CO, NO_2, and CH_2 in the near infrared region of the spectrum (1-10μ), under controlled conditions of pressure, composition and temperature	–
VIII-bbb	Kinetics of hydrogen-oxygen and hydrocarbon-oxygen reactions	U.S. Air Force Off. Scientific Res.	Univ. of Hull Hull, England	R. R. Baldwin	Supply definite answers to several of the controversial questions concerning the kinetics of oxidation and combustion of hydrogen and hydrocarbons	–
VIII-ccc	Basic combustion research – diesel engines	U.S. Army Tank Auto. Command	Univ. of Mich. Ann Arbor, Mich.	J. A. Bolt N. Henein	Learn more about ignition delay, rates of pressure rise and other combustion phenomena for highly supercharged diesel cylinders	30,000/yr
VIII-ddd	Thermal decomposition of hydrocarbons in a single pulse shock tube	Nat'l Bureau Standards	Nat'l Bureau Standards	W. Tsang	–	–
VIII-eee	High-temperature chemical information	Nat'l Bureau Standards	Nat'l Bureau Standards	J. J. Diamond	–	–
VIII-fff	Atomic reaction kinetics	Nat'l Bureau Standards	Nat'l Bureau Standards	J. T. Herron R. E. Huie	Make a systematic survey of the rates of reaction of ground state atomic oxygen with organic compounds	–
VIII-ggg	Effect of electric field on kinetics of an opposed jet diffusion flame	Nat'l Sci. Found.	Penn State Univ. Univ. Park, Pa.	P. M. Becker R. J. Heisohn	Identify the specific-chemical reactions that are important in a flame under the influence of an electric field	–

Table VIII-3. (Continued)

Project Key	Project or Contract Title	Sponsoring Organization and Contract No.	Research Organization	Principal Investigator	Objective or Scope	Funding, $
VIII-hhh	Applied chemical kinetics	State of Calif.	UCLA Los Angeles, Calif.	Chieh Chu	Study in an opposed jet diffusion flame the kinetics of combustion processes of interest to pollution control	–
VIII-iii	Fundamental study of the combustion of natural gas	American Gas Association	Inst. of Gas Tech. Chicago, Ill.	–	Investigate new principles and develop fundamental data to improve our understanding of the role of ions in flames, the formation of trace constituents in flames, and the effect of solids on combustion	–
VIII-jjj	Gas-solid dispense system	Aerofall Mills & Nat'l Res. Council	Aerofall Mills Ltd. Canada	R. R. Turner H. D. Goodfellow	Carry out fundamental examination of the d physical and chemical forces which influence the behavior of solid particles in gas streams	–
VIII-kkk	Formation of oxides of nitrogen in oscillating combustion	Sheffield City Corp. Clean Air Group	Dept. of Fuel Technology and Chem. Eng. Univ. of Sheffield Sheffield, England	T. D. Brown D. Thompson	Predict and measure oxides of nitrogen in oscillating combustion systems in the frequency range 600-1600 Hz	–
VIII-lll	Studies on the formation of oxides of nitrogen in combustion systems	–	Dept. of Fuel Technology and Chem. Eng. Univ. of Sheffield Sheffield, England	–	–	–
VIII-mmm	Bond dissociation energies in polyatomic molecules by kinetic methods	U.K. Science Res. Council	Univ. of Birmingham Birmingham, England	J. A. Kerr	Determine bond energies in hydrocarbons and heats of formation of some radicals	–

PRIORITY RANKING PROCEDURE FOR RESEARCH OPPORTUNITIES IN THE FUNDAMENTAL AND BROADLY APPLICABLE AREA

Philosophy of Priority Ranking for Fundamental Research

The rationale employed to priority rank R&D opportunities in the applied areas has been described previously in Chapter II. The significant point here is that applied-R&D opportunities accrued value, or priority, only by promising a direct and foreseeable route to a (roughly) predictable reduction in pollutant emissions. On this basis, research opportunities in the fundamental and broadly applicable area have no similar value: they are directed not so much towards achieving an immediate predictable reduction in pollutant emissions, but rather towards achieving an understanding of the problems or towards the accumulation of basic data pertinent to pollutant emissions from combustion sources.

It can be, and has been, argued that this is entirely appropriate: that the research opportunities in the fundamental and broadly applicable area *should* have no value in the context of this study. Such arguments are strongly supported by the historical fact that fundamental research in combustion has been at best loosely coupled to the design and development of combustion devices. At least on the surface, it appears that fundamental combustion research has been either unconnected with practical problems, or has served to explain, after the fact, the success of the equipment designer. It is also true that fundamentally oriented research undertaken at the present time is highly unlikely to influence the outcome of applied R&D within the 5-year research period considered in this study.

However, it can be argued that such a viewpoint is entirely short ranged, and, in the long range, is apt to greatly limit the ability to solve combustion-associated emission problems. While the combustion-equipment designer may draw on the "art" for support, rather than on the results of fundamental research, this art is strongly supported by previous fundamental research. Furthermore, examples, even though possibly isolated ones, can be found where the results of fundamentally oriented combustion research have directly contributed to the solution of engineering problems. Perhaps the strongest example in the pollution-oriented field is the fundamental work on the chemistry of the nitrogen-oxygen system.

Accepting the argument that fundamentally oriented combustion research is deserving of support within the context of this study, the problem remains as to how such research should be priority ranked. Clearly, any such ranking should reflect the major applications orientation of the Plan. The procedure adopted does reflect the applications orientation and has certain features which parallel the ranking of applied-R&D opportunities.

Ranking by Relevance to Applied-R&D Opportunities

The approach taken in assigning priority rank to the fundamental and broadly applicable research opportunities is based on their relevance to the set of applied-R&D opportunities. A quasiquantitative measure of the relevance was obtained by assigning a set of relevance numbers, ranging between 0 and 1, to each fundamental-research opportunity. Non-zero values were assigned when the fundamental-research opportunity had some bearing on an applied R&D opportunity. If the connection visualized was vague or remote (for example, the connection between basic chemical research on hydrocarbon-oxidation mechanisms and the emission of hydrocarbons from IC engines), a low value was assigned. Higher values were assigned where the fundamentally oriented research could make a direct contribution to the applied R&D. A relevance number of 1.0 was chosen to indicate that the results of the fundamentally oriented research were required for successful completion of the applied R&D.

Relevance numbers were assigned on the basis of expert judgment through consensus of three members of the study team with extensive background in both fundamental and applied combustion research. The values of the assigned relevance numbers ranged from 0 to 0.8.

Several schemes were investigated for assigning priority rank to the fundamentally oriented research opportunities by using the relevance numbers to "borrow" benefit or priority from the applied-R&D opportunities. The method finally chosen, on the basis that it yielded the most satisfying priority ranking and most closely paralleled the procedure used to rank the applied-R&D opportunities, was to "borrow" priority from the applied-R&D opportunities in proportion to the relevance numbers, and then sum the borrowed priority to give an *associated priority.*

Numerical Priority Scale of Associated Priority. The five priority ranks, A to E, of the applied-R&D opportunities were assigned numerical values of 16, 8, 4, 2, and 1, respectively. This logarithmic scale was chosen to avoid the elevation of a fundamental-research opportunity to a high priority rank by association with a large number of low-ranked applied-R&D opportunities. The products of the numerical values assigned to priority ranks for applied-R&D opportunities and the appropriate relevance numbers were then summed for each fundamentally oriented research opportunity by program elements (e.g., Central-Station Power Plants) to yield an associated-priority number. The 27 fundamental-research opportunities were then ranked in order of their associated-priority number, and grouped into five priority classes for each applied program element by assigning the 6 highest-ranked opportunities to the first priority, the next three groups of 5 to the second, third, and fourth priorities, and the final 6 to the fifth priority. The fundamental-research opportunities were then given overall priority rankings based on their total relevance to each applied R&D priority. A cummulative procedure was used in which, for example, relevance not used in assigning a research opportunity to the first priority class was applied to the second priority class. The cuts between priority classes were then made judgmentally.

Display of Associated Priority Numbers

Each fundamental and broadly applicable research opportunity described at the end of this chapter thus has 6 priority rankings: one for each of the five applied program elements and one for the overall program. This multiple ranking is used because a specific research opportunity may rank very high when viewed in terms of a single program element, and yet be ranked relatively low in terms of the overall program. Thus, the multiple ranking may be used to provide some additional insight into balancing the fundamental and applied programs.

ranging between 0 and 1, to each fundamental-research opportunity. Non-zero values were assigned when the fundamental-research opportunity had some bearing on an applied R&D opportunity. If the connection visualized was vague or remote (for example, the connection between basic chemical research on hydrocarbon-oxidation mechanisms and the emission of hydrocarbons from IC engines), a low value was assigned. Higher values were assigned where the fundamentally oriented research could make a direct contribution to the applied R&D. A relevance number of 1.0 was chosen to indicate that the results of the fundamentally oriented research were required for successful completion of the applied R&D.

Relevance numbers were assigned on the basis of expert judgment through consensus of three members of the study team with extensive background in both fundamental and applied combustion research. The values of the assigned relevance numbers ranged from 0 to 0.8.

Several schemes were investigated for assigning priority rank to the fundamentally oriented research opportunities by using the relevance numbers to "borrow" benefit or priority from the applied-R&D opportunities. The method finally chosen, on the basis that it yielded the most satisfying priority ranking and most closely paralleled the procedure used to rank the applied-R&D opportunities, was to "borrow" priority from the applied-R&D opportunities in proportion to the relevance numbers, and then sum the borrowed priority to give an *associated priority.*

Numerical Priority Scale of Associated Priority. The five priority ranks, A to E, of the applied-R&D opportunities were assigned numerical values of 16, 8, 4, 2, and 1, respectively. This logarithmic scale was chosen to avoid the elevation of a fundamental-research opportunity to a high priority rank by association with a large number of low-ranked applied-R&D opportunities. The products of the numerical values assigned to priority ranks for applied-R&D opportunities and the appropriate relevance numbers were then summed for each fundamentally oriented research opportunity by program elements (e.g., Central-Station Power Plants) to yield an associated-priority number. The 27 fundamental-research opportunities were then ranked in order of their associated-priority number, and grouped into five priority classes for each applied program element by assigning the 6 highest-ranked opportunities to the first priority, the next three groups of 5 to the second, third, and fourth priorities, and the final 6 to the fifth priority. The fundamental-research opportunities were then given overall priority rankings based on their total relevance to each applied R&D priority. A cummulative procedure was used in which, for example, relevance not used in assigning a research opportunity to the first priority class was applied to the second priority class. The cuts between priority classes were then made judgmentally.

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R&D Opportunity: VIII-1

Related to: VI-1, 2; VIII-3, 28; VIII-g, i, cc, pp, kkk, lll

Experimental and Theoretical Investigations of the Interactions and Coupling of the N_2 - O_2 System with Other Reactions and Species in Combustion Systems

Technical Objective and Approach

The objective is to achieve the ability to model NO_x in a combustor operating in the stoichiometric to fuel-rich region.

The approach should consist initially of attempting to integrate the known N_2 - O_2 system with some kind of a global model of the HC - O_2 system. This might be done by finding a measure of the reducing or oxidizing "power" of the overall fuel-air mixture and empirically relating this to observed NO_x concentrations. The experimental combustion equipment should be designed to yield a simple and well characterized flow. A flat-flame burner followed by a plug-flow zone is suggested.

Rationale and Incentive

NO_x models for fuel-lean systems are reasonably successful. That is not the case for fuel-rich systems, and it is suspected that the influence of the HC - O_2 reaction in the availability of O atoms may be responsible. A method of modeling the NO_x formation process in other than fuel-lean combustion systems is needed if analysis-design procedures are ever to be used in optimizing combustion for NO_x emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$2,000
R&D Time Range: 1-5 years

Recommended 5-year Funding, 1000's: $1,000

Funding by Fiscal Year, $1000's	'69-70	'71	'72	'73	'74	'75	'76+
	X	200	200	200	200	200	100/yr

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	1	3	2	3

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-2

Related to: III-10, 11; VIII-g

Experimental Studies of the Contribution of Combined Nitrogen in Fuels to the Emission of NO_x

Technical Objective and Approach

The objective is to determine the contribution of chemically bound nitrogen in the fuel on NO_x profiles in a combustor, particularly whether the chemically bound nitrogen contributes to the formation of NO_x levels above that attributable to thermal fixation.

The approach should involve the burning of nitrogen-free fuels doped with various organic nitrogen compounds in a flat-flame burner and sampling for NO_x. Combustion air should be replaced by argon-oxygen mixtures for many of the experiments.

Rationale and Incentive

Nitrogen in the fuel may be thermally equilibrated during the combustion process, or such chemically bound nitrogen might be directly oxidized to NO_x at levels substantially in excess of the thermal equilibrium, particularly in low-temperature combustion processes. When nitrogen-containing coal or heavy oil is the fuel, the contribution of the chemically bound nitrogen in the fuel to NO_x emissions may be highly significant and may interfere with schemes for reducing NO_x levels by reducing the peak system temperature to low values.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$500

R&D Time Range: 1-5 years

Recommended 5-year Funding, 1000's: $375

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	100	75	50	50	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	1	5	–	–

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-3

Related to: VIII-bb, gg, ll, nn

Investigation of the Kinetics of the N_2 - O_2 (only) System

Technical Objective and Approach

It is not recommended that any effort be devoted to the study of NO_x kinetics in systems restricted to species derivable from N_2 and O_2, as such systems are sufficiently well understood for pollution-related purposes.

Rationale and Incentive

Adequate elementary rate constants are available for important elementary reactions in the N_2 - O_2 system. Models for NO_x emissions seem adequate for systems that approximate the N_2 - O_2 systems (i.e., fuel-lean systems). For fuel-rich systems, models are not so good, but this is because of the inadequate treatments of the hydrocarbon-oxygen systems and their coupling with the N_2 - O_2 system. That situation will not be remedied by further study of the N_2 - O_2 system.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: None
R&D Time Range: None

Recommended 5-year Funding, 1000's: $0

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	–	–	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
nr	nr	nr	nr	nr

Relative Overall Priority Rating: nr (not recommended)

R&D Opportunity: VIII-4 Related to: VIII-9; VIII-bbb, ddd, fff

Experimental Determinations of the Global Kinetics of Dilute HC - O_2 Systems and Kinetics in Quenched Systems

Technical Objective and Approach

The objective is the measurement of gross rates of removal of hydrocarbons and other carbon-containing species in dilute and quenched systems.

The approach should include measurements of rates of disappearance as a function of temperature, pressure, concentrations, and perhaps concentrations of a few other controllable species (CO, CO_2, H_2O, O_2) and wall effects. Interpretation of results in terms of a mechanism is not intended. The results need not be expressed in a conventional rate expression to be useful.

The research should involve measurements in a variety of systems, such as the tail gases from ordinary flames, a heated plug-flow system, packed reactors, and well-stirred reactors. Sampling and analysis should be the major measurement techniques. Considerable attention should be devoted to the problem of defining the limitations of the results, primarily by exploring a wide range of variables.

Rationale and Incentive

Global kinetic data may be useful in the design of combustion equipment to minimize the emission of HC, CO, and related reducing species.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$500

R&D Time Range: 2-5 years

Recommended 5-year Funding, 1000's: $400

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	100	100	100	100	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
3	3	3	3	1

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-5

Related to: VII-4; VIII-4, 9; VIII-i, t, w, aa

Experimental Investigation of Wall-Quenching Phenomena as Related to the Formation of Pollutants

Technical Objective and Approach

The objective is to determine the relation of wall quenching in various turbulent environments to the production of pollutants by a burning mixture.

Two approaches are suggested. In the first approach, the combustible mixture should be ignited at one end of a duct, and the production of various species by the resulting combustion should be determined. The area-to-volume ratio should be varied by inserting axial rods. At the igniting end, a thin burst diaphragm could be used to isolate temporarily the flash tube from a large pressure-stabilizing volume filled with inert gas.

In the second approach, a combustion bomb should be used to study wall-quenching effects, using vaporized gasoline, vaporized kerosene, and propane. The bomb should be of a type in which turbulence of controlled scale and intensity can be generated. Provision should be made for preheating the bomb and starting the explosion at other than atmospheric pressure. Provision should also be made for changing the surface-to-volume ratio. In addition to data on initial and final composition of all species of interest, data should be obtained on turbulent flame speed, final temperature, and pressure.

Rationale and Incentive

Data relating wall-quenching phenomena to formation of pollutants would permit specifying the conditions under which pollution production (incomplete combustion) by wall quenching can be minimized.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$800

R&D Time Range: 3-6 years

Recommended 5-year Funding, 1000's: $735

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	85	200	150	150	150	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
3	–	4	4	1

Relative Overall Priority Rating: 4

R&D Opportunity: VIII-6

Related to: VIII-7, 9; VIII-bbb

Experimental Investigation of the Kinetics of Oxygenated Intermediates and Their Destruction by Oxidation

Technical Objective and Approach

The objective is to characterize the formation and destruction of oxygenates in combustion processes.

One approach should be studies of the oxidative destruction of such materials in moderately hot, low-oxygen environments. The influence of other species, such as H_2O, CO, and CO_2, should be investigated.

Rationale and Incentive

It is suspected that oxygenates are contributors to diesel exhaust odors and odors from other combustion sources. Better knowledge of their behavior will be useful in alleviating the problem.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$300
R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $150

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	50	50	50	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
5	–	4	3	1

Relative Overall Priority Rating: 4

R&D Opportunity: VIII-7

Related to: VII-8; VIII-6, 9; VIII-gg

Experimental Investigation of the Contribution of Specific Fuel Constituents to Odor Production in the Combustion Process

Technical Objective and Approach

The objective is to determine what, if any, chemical species in diesel fuels contribute in a major way to the formation of odorants in diesel exhaust.

The approach should be to operate a diesel engine with well-defined fuels, possibly with a "synthetic" fuel selected for low odor production and doped with specific chemical species to be investigated.

Rationale and Incentive

It is suspected that specific chemical species in diesel fuels contribute as such to the characteristic diesel exhaust odor. It is possible that specific chemical species in the fuels may also contribute in a major way to the formation of partial-oxidation products which are strong odorants. If such fuel components are found to exist, refining processes might be altered to eliminate them from the fuel.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$400
R&D Time Range: 1-4 years

Recommended 5-year Funding, 1000's: $150

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	50	50	50	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
–	–	–	5	1

Relative Overall Priority Rating: 4

R&D Opportunity: VIII-8 Related to: VIII-bb

Investigations of the Kinetics of the CO - O_2 - H_2 (only) System

Technical Objective and Approach

No work is recommended, as the current understanding of this system is adequate for the purposes here considered.

Rationale and Incentive

Reasonably adequate information about important reactions of CO in combustion systems is available. The major problem lies in integrating this information with information relative to other processes also occurring. Therefore, no study is recommended of CO combustion reactions as such.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: None
R&D Time Range: None

Recommended 5-year Funding, 1000's: $0

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	–	–	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
nr	nr	nr	nr	nr

Relative Overall Priority Rating: nr (not recommended)

R&D Opportunity: VIII-9

Related to: VIII-4, 6, 8, 10; VIII-ss, bbb, iii

Fundamental Experimental Studies of HC Oxidation Kinetics

Technical Objective and Approach

The objective is to develop a better understanding of the kinetics and mechanisms of hydrocarbon oxidation.

The approach should be broad in scope because the HC - O_2 system is so little understood. Relevant approaches range from conventional batch-reactor studies to studies with shock tubes. This research will of necessity include some study of pyrolysis reactions.

Rationale and Incentive

A better understanding of the HC - O_2 system is basic to a scientific understanding of the combustion process, including the emission of many of the pollutants of current concern. Because of the complexity of the subject area, practical results cannot be expected at an early date; in fact, it is not feasible even to suggest specific techniques or subareas at this time. The field of study extends to considerations well beyond pollution, and activity in this field derives support from other interests.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$1,000
R&D Time Range: 1-5 years

Recommended 5-year Funding, 1000's: $250

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	50	50	50	50	50	50/yr

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
4	3	4	4	4

Relative Overall Priority Rating: 5

Related to: VIII-9; VIII-kk

R&D Opportunity: VIII-10

Experimental and Theoretical Studies of the Kinetics and Mechanism of HC Pyrolysis Reactions

Technical Objective and Approach

The objective is a better, broader knowledge of pyrolysis reactions.

Because the area is broad and largely unexplored, no specific goals or approaches can be suggested. All things considered, a low level of support seems advisable until specific pollution-related goals and approaches can be specified.

Rationale and Incentive

Pyrolyses are poorly understood and yet basic to any scientific understanding of the combustion process. These reactions are important in many processes, and support for research also comes from other interests not oriented to pollution abatement.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$500

R&D Time Range: 1-5 years

Recommended 5-year Funding, 1000's: $250

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	50	50	50	50	50	50/yr

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	2	4	4	2

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-11

Related to: V-5; VII-6; VIII-12

Experimental Investigation of the Contribution of PNA Contained in Solid and Liquid Fuels to the Emission of PNA

Technical Objective and Approach

The objective is to measure PNA and other important specie profiles in PNA-doped or PNA-fueled flames and, thus, follow the destruction of PNA in the combustion process. Conditions leading to the most rapid or complete destruction of PNA should be sought, and the influence of the main combustion process on the destruction should be determined.

The approach should be to conduct investigations using a flat-flame burner followed by a plug-flow zone, with the entire region between the burner face and some far-downstream position being sampled for PNA and any other species which are identified to be important in the destruction of PNA. Such conventional variables as fuel type and fuel-air ratio should be examined, as well as residence time, flame temperature, temperature decay, and the nature of the PNA molecule.

Rationale and Incentive

Coal and some liquid fuels may contain PNA. It will be useful to have information about the behavior of fuel-supplied PNA and to learn how it may differ from the behavior of other fuel species in the flame. Ultimately, such understanding should lead to capability for designing combustion devices for minimum PNA emission.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$200

R&D Time Range: 1-3 years

Recommended 5-year Funding, 1000's: $100

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	50	50	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	–	3	–	–

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-12

Related to: V-5; VII-6; VIII-9, 11; VIII-kk

Experimental Studies of the Formation and Destruction of PNA in Flames

Technical Objective and Approach

The objective is to obtain information about PNA profiles in flames. Conditions favorable and unfavorable to their formation and destruction should be sought, and global reaction rates obtained. Ultimately, kinetic mechanisms may be identified.

The approach suggested is sampling from various regions in the flame of a flat-flame burner. The fuel employed would be a variable, as would the fuel-air ratio and possibly the presence of diluents and the initial reactant temperature.

Rationale and Incentive

Little information is available on the way in which PNA is formed in combustion, or on its subsequent destruction. It is possible that better knowledge of these processes could permit the design of combustion devices optimized with respect to PNA emissions.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$750

Recommended 5-year Funding, 1000's: $500

R&D Time Range: 2-5 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	100	100	100	100	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
3	–	1	3	1

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-13 Related to: V-1; VIII-14; VIII-mm

Experimental and Theoretical Investigations of the Formation of Soot in Flames

Technical Objective and Approach

The objective is to gain knowledge of the conditions and processes leading to the formation of soot in flames and combustion reactions, with the expectations that ultimately such knowledge will lead to an ability to design combustion systems which do not emit soot.

In view of the primitive state of knowledge concerning soot formation, a highly specific approach cannot be suggested. However, examination of simple, well-characterized flames using modern sampling and analytical techniques is the obvious beginning. Searches for the precursors of visible soot, studies of the nucleation and growth process, and examinations of the relationships of soot to other flame species, particularly PNA, seem to be indicated.

Rationale and Incentive

Some features of the soot-formation process, or factors that influence it, are known, but the understanding is not adequate to permit predictions. For example, the ability of various diluents, including flue gas, to suppress soot formation has been known for many years, but no satisfactory mechanism or even empirical correlation has been suggested. As the most likely chemical structure for soot is a very large PNA molecule, the relationship between soot and the lower molecular weight PNA's emitted by combustion systems deserves study.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $300-$1,000

R&D Time Range: 2-8 years

Recommended 5-year Funding, 1000's: $375

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	75	75	75	75	75	150

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
4	3	2	3	2

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-14 Related to: VIII-13

Investigations of the Kinetics and Mechanism of Soot Combustion in Flames and Post-Combustion Gas Streams

Technical Objective and Approach

The objective is to learn something of the kinetics of combustion of soot, including, if possible, precursors to visible soot, with the ultimate intent of being able to specify the conditions needed to consume such flame species if their formation cannot be prevented.

In view of the fine particulate nature of soot, most experimental work will of necessity approach the problem through flame studies. Because of the primitive state of knowledge in this area, highly specific approaches and research goals cannot be stated.

Rationale and Incentive

Combustion of comparatively pure carbon has been studied in the past but soot has received little attention. Some empirical data have been obtained on soot burnout (e.g., from the work at Sheffield University) but no correlation other than the most general influence of oxygen and temperature seems to have been advanced.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $250-$1,000

R&D Time Range: 2-5 years

Recommended 5-year Funding, 1000's: $500

	'66-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	100	100	100	100	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
4	3	3	3	2

Relative Overall Priority Rating: 4

R&D Opportunity: VIII-15

Related to: VIII-ff, ii, oo

Analytical and Experimental Studies of the Kinetics of Sulfur Oxidation in the Combustion Process

Technical Objective and Approach

The objective is to clarify existing information on sulfur oxidation and to determine the interactions with other species in the flame and post-flame region.

Approaches should include studies of reactions in flames and continuous-flow nonflame systems.

Rationale and Incentive

Sulfur oxidation level may have some influence on the effectiveness of downstream controls. Kinetics may be important in that relation. It must be emphasized that combustion modifications cannot change the fact that the combustion of sulfur-containing fuels will lead to the emission of sulfur species in the combustion gases.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$300

R&D Time Range: 1-2 years

Recommended 5-year Funding, 1000's: $150

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	75	75	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	–	–	–	–

Relative Overall Priority Rating: 5

R&D Application: VIII-16

Investigations of the Chemistry of Lead in Combustion Processes

Technical Objective and Approach

No study is recommended, as no useful result can be foreseen.

Rationale and Incentive

Lead is emitted from IC engines burning leaded gasoline, and this fact cannot be altered by any foreseen possibility for appropriate modification of the combustion process. It must be emphasized, however, that combustion research aimed at eliminating the need for lead, or at replacing lead by a less obnoxious additive, might provide valuable results.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: None
R&D Time Range: None

Recommended 5-year Funding, 1000's: $0

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	–	–	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
nr	nr	nr	nr	nr

Relative Overall Priority Rating: nr (not recommended)

R&D Opportunity: VIII-17 **Related to: VIII-18, 19; VIII-c, q, x**

Analytical and Experimental Investigation of the Influence of Inhomogeneities on Pollutant Formation in Droplet Flames and Pulverized-Coal Flames

Technical Objective and Approach

The objective is to determine the effect of scale of inhomogeneity (e.g., premixed fuel and air versus the same fuel in droplets) on chemical behavior and local temperatures and thus on the formation of pollutants.

The approach should be to conduct research with various laboratory rigs. Experimental design and instrumentation would be a major problem in this research.

Rationale and Incentive

Practical combustion systems burning solid and liquid fuels have obvious inhomogeneities. These inhomogeneities may cause substantial deviations between, for example, the overall fuel-air ratio and the fuel-air ratio in those regions where combustion is occurring. Macroinhomogeneities of this character, due for example to imperfect mixing of gaseous fuels and air, are suspected as being the cause of certain pollutants being emitted in concentrations greater than expected. Knowledge of the effects of inhomogeneity at the scale of oil droplets or pulverized coal particles on the behavior of a system would be useful in applying data from homogeneous systems to heterogeneous ones, or in showing that such applications are not feasible.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $100-$400
R&D Time Range: 1-4 years

Recommended 5-year Funding, 1000's: $150

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	75	75	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	–	4	–	–

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-18 Related to: V-1, 11; VII-3-7, VIII-17, 19; VIII-c, q, x

Experimental Investigation of the Relation of Size Distribution and Relative Velocity of Burning Droplets and Particulates to the Formation of Pollutants

Technical Objective and Approach

The objective is to determine the relation of droplet (and particle) size distribution and relative velocity of liquid fuel droplets (and pulverized-coal particles) to the formation of pollutants.

The approach should include experimental measurements in a plug-flow furnace with fuel droplets (gasoline, No. 2 heating oil, heavy fuel oil) and pulverized-coal particles (P.C. and devolatilized P.C.) uniformly distributed over the cross section. Alternatively, more conventional types of combustors might have to be used with close delineation and study of a specific flow path with a controllable path history. Provision must be made for varying droplet or particle size and distribution and the relative velocity of droplets or particles and the air.

Rationale and Incentive

With respect to studies of liquid fuels, the results of this program may permit specification of the optimum droplet size distribution to minimize pollution. It might also suggest new types of spray formation. The work may establish the effect on the formation of pollutants of having fuel in droplet form rather than vapor form.

In the case of pulverized coal, this program should establish the effect of particle size distribution on pollutant emissions. In combination with the results of other studies, this program should lead to an understanding of the interaction of particulate-matter burning and volatile-matter burning on pollutant formation.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $800-$1,150 Recommended 5-year Funding, 1000's: $1,000
R&D Time Range: 4-6 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	200	200	200	200	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	1	1	1	4

Relative Overall Priority Rating: 1

R&D Opportunity: VIII-19 **Related to: V-1; VIII-17, 18; VIII-c, o, x**

Experimental Studies of Single or Small Number of Burning Droplets and Particles to Determine the Relation of Size and Other Factors to Pollutant Formation

Technical Objective and Approach

The objective is to gain an understanding of pollution-related aspects of droplet and particle burning by observing the burning, in a hot environment, of single droplets and particles, or small numbers of them, in the size range common to fuel sprays.

The approach should be based on the projection of droplets and particles through various hot environments. Measurement and analysis are expected to be difficult, and development of suitable techniques will be an important part of the program. It is essential that the size, size distribution, and relative velocity of droplets (or particles) and the environment be in the range characteristic of prototype combustors.

Rationale and Incentive

Research to improve the understanding of the relation of the life history of a droplet or particle, or an array of them, to pollutant formation, and of the characteristics of the life history that lead to particulate formation should lead to reducing these emissions. For liquid fuels, the results could suggest changes in spray nozzles to alter droplet size distribution in a beneficial manner. For pulverized coal, an understanding of the relation of the life history of particles to pollutant formation should aid in formulating the proper burning conditions and size distribution of the fuel.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $175-$350

R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $325

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	75	75	75	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
3	2	2	2	2

Relative Overall Priority Rating: 3

R&D Opportunity: VIII-20

Experimental Investigation of the Burning Process of a Solid-Fuel Particle in Simulated Fluidized or Fixed Beds

Technical Objective and Approach

The objective is to gain understanding of fluidized-bed combustion and associated reactions by determining the life history of burning fuel particles in simulated fluidized beds.

The approach should involve use of a rig in which the particles are fixed and the gases move through the array. The particle of interest should be studied in detail as time progresses. Input gases should be varied with respect to temperature, composition, and flow rate. Off-gases from the array could be analyzed. With proper insulation and refractory walls (possibly preheated before a test array is inserted), it should be possible to keep the equipment relatively small.

Rationale and Incentive

Research to provide insight into the reaction processes in a fluidized bed and to permit identifying the stages of the process in which pollutants are formed, destroyed, or captured, in combination with classical information on fluidized beds, should help to specify optimum operating conditions for low emissions. This, of course, is directed primarily toward the elimination of SO_2 and SO_3 from the burning of coal, and possibly the reduction of NO_x.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $225-$350
R&D Time Range: 2-3 years

Recommended 5-year Funding, 1000's: $225

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	125	100	–	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	–	3	–	–

Relative Overall Priority Rating: 1

R&D Opportunity: VIII-21 Related to: VIII-j, iii

Experimental Determination of the Effect of Composition Gradients and Gaseous Fuel Type on the Production of Pollutants in Laminar Diffusion Flames

Technical Objective and Approach

The objective is to determine the effect of composition gradients and fuel type on the formation of pollutants, especially particulates, in laminar diffusion flames with gaseous fuels.

The approach should involve building a relatively simple enclosed nonturbulent-diffusion-flame rig. Initially attention should be focused on the effect of fuel-air gradient and temperature on the formation of various pollutants. Then the effect of fuel type (considering several pure hydrocarbons from methane through butane) on the production of pollutants should be investigated. After preliminary tests have been conducted with NO_X, CO, etc., concentration should be on production of particulate manner.

Rationale and Incentive

A better understanding of the factors involved in particulate growth and decay as related to fuel composition, as well as composition gradients, would be of particular value for the design of residential heating units. The most obvious effect of fuel type is that on smoke production. Reformulation of some fuels might be indicated. The information should also help to clarify the structure of turbulent diffusion flames.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $200-$550

R&D Time Range: 3-4 years

Recommended 5-year Funding, 1000's: $270

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	90	60	60	60	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
5	2	3	2	–

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-22

Related to: V-1, 2, 3; VIII-21; VIII-y, iii

Experimental Investigation of the Effect of Turbulence and Gaseous Fuel Type on Pollutant Formation in Turbulent Diffusion Flames

Technical Objective and Approach

The objective is to determine the effect of turbulence and fuel type on the production of pollutants in turbulent diffusion flames with gaseous fuels.

Probably a large rig should be used for this study, especially if the rate of effort is minimum. Turbulence scale and intensity should be the major variables considered. The effect of fuel type should also be investigated. Special instrumentation might have to be developed for solving problems related to the effect of "unmixedness" on the production of pollutants. Attention should be given to the part that flame stability plays in the production of pollutants.

Rationale and Incentive

Many industrial flames are of the turbulent-diffusion-flame type. This research should provide guidelines for the optimization of turbulent conditions in gaseous-fuel combustion systems to minimize pollutant emission and form a basis for studies of other fuels burned in like manner.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $800-$1,550

R&D Time Range: 4-5 years

Recommended 5-year Funding, 1000's: $1,025

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	275	225	225	150	150	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	1	1	1	3

Relative Overall Priority Rating: 2

R&D Opportunity: VIII-23 **Related to: VIII-21, 24**

Experimental Determination of the Effect of Pressure on Pollutant Formation in Laminar Diffusion Flames

Technical Objective and Approach

The objective is to determine the effect of pressure on the formation of pollutants in laminar diffusion flames of vaporized liquid fuels.

The approach should be to use a modified type of nonturbulent-diffusion-flame rig. Because fuels of interest include vaporized gasoline and kerosene, a provision for heating must be made. In addition, the system must be capable of being pressurized. It is known that pressure has an effect on soot formation, and probably on the formation of other pollutants as well.

Rationale and Incentive

A fundamental understanding of pollutant formation from higher hydrocarbons under various pressure conditions would be helpful in understanding, and ultimately in reducing, the formation of pollutants in diesel and gas-turbine engines.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $175-$300

R&D Time Range: 2-4 years

Recommended 5-year Funding, 1000's: $250

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	100	75	75	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
5	–	–	4	4

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-24 Related to: VIII-23

Experimental Investigation of the Effect of Pressure on Pollutant Formation in Turbulent Diffusion Flames

Technical Objective and Approach

The objective is to determine the effect of combustion-chamber pressure on the formation of pollutants by turbulent diffusion flames of vaporized liquid fuels.

The approach should be to examine, in an appropriate rig, the effects of pressure on a turbulent diffusion flame. Gasoline, kerosene, and propane should be included in this study. Turbulence scale and intensity should be varied over a range comparable to that typical for industrial units and the extent of "unmixedness" and its influence determined. The problems of studying the details of "unmixedness" and its effects will be complicated by the pressure (if only because the size scale for measurement decreases with increasing pressure).

Rationale and Incentive

Results should aid directly in the reduction of pollutants from gas-turbine-type combustors and indirectly in the reduction of pollutants from IC engines.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $400-$500

R&D Time Range: 3-4 years

Recommended 5-year Funding, 1000's: $500

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	200	150	150	–	–	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
–	–	–	1	2

Relative Overall Priority Rating: 5

R&D Opportunity: VIII-25 Related to: III-5; V-1, 2, 3; VI-1, 2, 3, 4, 5; VIII-26; V-iii

Experimental Determination of the Relation of Pollutant Output to Path History Along Flow Paths Typical of Combustion Systems Burning Premixed Gaseous Fuels

Technical Objective and Approach

The objective is to determine the relation of pollutant output to the flow path history typical for combustion systems burning premixed gaseous fuels.

The approach should include measurements to determine the production of pollutants as a function of flow path history in plug-flow combustors simulating path conditions in actual furnaces burning premixed gaseous hydrocarbon fuels. Specifically, natural gas, methane, ethane, propane, butane, and ethylene should be studied as fuels. The volatile gases driven off by rapid heating of coal should also be investigated. The primary variables considered should be mixture ratio, fuel type, and intensity and scale of turbulence. The effects of change in cooling rate and firing rate should also be examined. Primary measurements should be temperature, velocity, and composition (O_2, CO_2, CO, N_2, input fuel, NO_x, C_nH_m, particulates). At least one rig should be of a size commensurate with prototype practice.

Rationale and Incentive

Considerable reduction in pollutant emissions might be achieved if it were possible to specify conditions along flow paths for minimizing pollutant formation. The results from the burning of coal volatiles might lead to new concepts for pulverized-coal-burner design to minimize pollution. Results should also be applicable in a more basic manner to diffusion-flame combustion systems and be of value in studies of global kinetics.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $500-$1,500 **Recommended 5-year Funding, 1000's:** $1,325
R&D Time Range: 4-6 years

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	275	225	225	300	300	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
2	2	1	1	4

Relative Overall Priority Rating: 1

R&D Opportunity: VIII-26

Related to: VI-1, 2, 3, 4

Experimental Determination of the Relation of Pollutant Output to Path History Along Flow Paths Typical of Combustion Systems Burning Vaporized Hydrocarbons at Pressures Other Than Atmospheric

Technical Objective and Approach

The objective is to determine the effect of pressure on the relation of pollutant output to flow path history typical for vaporized fuel in hydrocarbon combustors operating at pressures other than atmospheric.

The approach should include operation of plug-flow combustors over a range of pressures sufficient to give data pertinent to both gas-turbine operation and IC-engine operation. The main variables should be fuel type (vaporized gasoline, vaporized kerosene, propane), mixture ratio, and pressure. The effects of turbulence and cooling rate should also be examined. Primary measurements should be temperature, velocity, and composition.

Rationale and Incentive

Pressure is known to have an influence on the combustion process. For example, the color of propane-air flames changes from blue to yellow as the pressure is increased from 1/4 to 4 atm. In view of the importance of combustion at elevated pressures in the gas turbine and IC engine, some understanding of the influence of pressure on pollutant emissions is desirable. The data obtained by this research, in combination with data from other programs giving more details on effect of turbulence, etc., would permit specifying the path conditions which minimize pollutant production in pressurized combustion systems.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $350-$950

R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $800

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	250	175	175	100	100	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
–	–	–	1	2

Relative Overall Priority Rating: 4

R&D Opportunity: VIII-27

Related to: III-2, 3, 4; IV-1, 2, 5; V-6, 7, 8; VI-2

Experimental Determination of the Effects of Addition of Recirculated Combustion Products, Secondary Air, and/or Supplemental Fuel on Pollutant Formation

Technical Objective and Approach

The objective is to determine the effect on pollutant production of the addition of recirculated combustion products, secondary air, and/or supplemental fuel at various stages of combustion of premixed gaseous fuels.

The approach should be to employ a plug-flow combustor rig with special provision for injecting the various test gases uniformly across various sections. Natural gas and propane are suggested as fuels. Primary measurements should be of temperature, velocities, and composition. Provision should be made for generating products of combustion and cooling them in varying amounts. For the air injection, provision should be made for heating. The injection of supplemental fuel at various stages of combustion should also be examined. Finally, the effect of interstage cooling of the products is also of great importance and should be examined.

Rationale and Incentive

There is considerable evidence that the optimum amount of recirculation of combustion products will minimize pollution. The suggested research should help define this optimum for premixed gaseous flames and provide guidelines for using recirculation for other types of combustors. The results probably will also furnish a guide to the potential benefits and the optimum use of two-stage and multi-stage combustion to minimize air pollution. Information would also be obtained on the beneficial or deleterious effects of rapid air quenching. Finally, the results of the fuel-injection tests might reveal two-stage combustion possibilities. However, this information may be more valuable in highlighting the deleterious effect of supplying fuel in the wrong stage of the combustion process.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $400-$800

Recommended 5-year Funding, 1000's: $650

R&D Time Range: 3-6 years

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	X	200	150	150	75	75	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	1	1	1	3

Relative Overall Priority Rating: 1

R&D Opportunity: VIII-28

Related to: IV-1, 2, 3, 4, 5; VIII-1; VIII-y

Experimental Investigation of Nitrogen Oxide and Other Pollutant Formation in Large Industrial-Size Flames

Technical Objective and Approach

The objective is to determine the influence of design and operating variables pertinent to natural-gas-, heavy-fuel-oil-, and pulverized-coal-fired diffusion-flame burners and furnaces of industrial or commercial size on the concentration of nitrogen oxides and other pollutants in the exhaust gases.

The approach should be to determine the production of NO_x, CO, particulates, and other pollutants in the exhaust gases and at other critical regions in combustion systems of industrial or commercial size. Pertinent data on flow velocities, temperature, and gas composition should also be obtained. Burners resembling commercially available units, but with more precisely known and controllable characteristics, should be used. Reasonable levels of thermal loads should be applied to the furnaces. Phenomenological explanation of the experimental results, leading to improvements in designs directed toward minimizing pollution, should be sought. The results should be compared with existing mathematical models of pollution production in furnaces.

Rationale and Incentive

The results of this program should reveal possibilities for relatively straightforward and simple design changes in present commercial and small industrial combustors and in firing practice to minimize pollutant production. Furthermore, the results should reveal the proper direction for development of new designs of this equipment. Because optimum performance is related to such concepts as recirculation and two-stage combustion, direction should also be given to fundamental and applied programs related specifically to these concepts.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $425-$800

R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $675

	'69-70	'71	'72	'73	'74	'75	'76+
Funding by Fiscal Year, $1000's	–	175	125	125	125	125	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
1	1	1	4	–

Relative Overall Priority Rating: 2

R&D Opportunity: VIII-29

Related to: VIII-17, 18, 21, 22

Preparation of a Monograph and Operation of an Information Center on Turbulence Aspects of Typical Combustor Flow Systems

Technical Objective and Approach

The objective is to produce a monograph on the turbulence aspects of typical practical combustion systems and to promote the interchange of information in this area among various NAPCA-sponsored research teams and others.

The approach should be to establish a team with responsibility for coordinating the turbulence aspects of all NAPCA-sponsored fundamental research programs. The team should serve as a source of information on the turbulence characteristics of practical combustors, supply information on the various ways to model or scale turbulence characteristics for various design approaches being considered, and produce a monograph covering the subject. Some small amount of experimental work will probably be required, including field measurements of turbulence in various combustion systems.

Rationale and Incentive

One factor common to all industrial combustion systems is the presence of turbulence. A rather extensive waste of effort would result if each research team were required to investigate the turbulence conditions typical to their areas of interest. Coordination and exchange of research results on turbulence aspects of combustion would reduce the overall cost and loss of time associated with duplicate efforts.

In addition to the coordinating effort, the overview provided by the program should produce some empirical conclusions relating turbulence characteristics to pollutant production that could be put into use rather rapidly in reducing pollutant emissions of combustion systems.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $325-$600

R&D Time Range: 5 years

Recommended 5-year Funding, 1000's: $600

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	–	120	120	120	120	120	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
4	2	2	2	3

Relative Overall Priority Rating: 2

R&D Opportunity: VIII-30

Related to: VIII-17, 18, 19

Preparation of a Monograph and Support of an Information Center on Atomization, Droplet Trajectories, and Droplet Burning

Technical Objective and Approach

The objective is to provide a source for current information on droplet production, trajectory, evaporation, and burning.

The approach should involve compiling information available in the literature, analyzing the data found, and making necessary calculations for the writing of an up-to-date monograph on the subject. The writer of the monograph could also provide consultation during the program, and update the monograph at the end of a specified five-year period.

No experimental work is contemplated.

Rationale and Incentive

Preparation of a monograph on droplet production, trajectory, evaporation, and burning would eliminate the necessity for multiple independent reviews of the literature by the various researchers working in this area. Establishing an information center would provide for updating the information and for interpretation.

Estimated R&D Cost & Time

R&D Cost Range, 1000's: $250-$500

R&D Time Range: 3-5 years

Recommended 5-year Funding, 1000's: $425

	'69-70	71	72	73	74	75	76+
Funding by Fiscal Year, $1000's	X	100	100	75	75	75	–

Evaluation

Associated Priority Ranking:

III Power Plants	IV Industrial Processing	V Industrial, Commercial, Residential	VI Continuous-Combustion Engines	VII Internal-Combustion Engines
4	2	2	2	1

Relative Overall Priority Rating: 2

R&D Opportunity: VIII-New Concepts

Provision for Exploring New Concepts and New Research Opportunities that Evolve from the Program and Accelerating Fundamental and Broadly Applicable Combustion Research that Promises to Yield Insight or to Solve Problems Associated with Applied Research

Technical Objective and Approach

The objective is to provide for long-range flexibility in the research program to enable APCO to take advantage of opportunities in the fundamental and broadly applicable areas that are not presently evident, but which can arise during the course of this program.

The approach should be to make specific provisions in the research program to explore new research concepts and to accelerate research in areas which promise to improve the understanding or to solve problems associated with the reduction of pollutant emissions. The merits of specific research opportunities should be evaluated as they evolve.

Rationale and Incentive

As the research and development activities directed towards control of pollutant emissions from energy-conversion-combustion sources progress, opportunities for research work in the fundamental and broadly applicable areas will arise. Such new opportunities may be associated with problems encountered in applied R&D activities, with new ideas for research, with the uncovering of gaps in knowledge and understanding by continuing research efforts, or by the addition of new pollutants to those of current major concern.

Support of fundamental and broadly applicable research in such newly uncovered areas has the potential of speeding the development of controls, preventing wasted effort in unpromising fields, and reducing the duplication of effort which otherwise might take place.

Recommended Funding Allocation

	'71	'72	'73	'74	'75	
Funding by Fiscal Year, $1000's	–	150	200	250	300	5-year Funding, 1000's: $900

Evaluation

This R&D Opportunity is unranked. The evaluation and funding level for each specific research opportunity must be determined when the opportunity is identified. The suggested funding level anticipates effort on several research opportunities.

Relative Priority Rating: N

TABLE VIII-4. SUMMARY OF PRIORITIES

FUNDAMENTAL AND BROADLY APPLICABLE COMBUSTION RESEARCH

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
1	VIII-18 Experimental Investigation of the Relation of **Size Distribution** and Relative **Velocity of Burning Droplets and Particulates** to the Formation of Pollutants	X	200	200	200	200	200	1,000	–
1	VIII-20 Experimental Investigation of the **Burning Process of a Solid-Fuel Particle** in Simulated Fluidized or Fixed Beds	X	125	100	–	–	–	225	–
1	VIII-25 Experimental Determination of the Relation of Pollutant Output to **Path History along Flow Paths** Typical of Combustion Systems Burning Premixed Gaseous Fuels	–	275	225	225	300	300	1,325	–
1	VIII-27 Experimental Determination of the Effects of **Addition of Recirculated Combustion Products, Secondary Air, and/or Supplemental Fuel** on Pollutant Formation	X	200	150	150	75	75	650	–
	Totals, Priority 1		800	675	575	575	575	3,200	

TABLE VIII-4. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
2	VIII-22 Experimental Investigation of the Effect of **Turbulence** and **Gaseous Fuel Type** on Pollutant Formation in **Turbulent Diffusion Flames**	X	275	225	225	150	150	1,025	–
2	VIII-28 Experimental Investigation of **Nitrogen Oxide** and Other Pollutant Formation in **Large Industrial-Size Flames**	–	175	125	125	125	125	675	–
2	VIII-29 Preparation of a **Monograph** and Operation of an **Information Center on Turbulence** Aspects of Typical Combustor Flow Systems	–	120	120	120	120	120	600	–
2	VIII-30 Preparation of a **Monograph** and Support of an **Information Center** on **Atomization, Droplet Trajectories, and Droplet Burning**	X	100	100	75	75	75	425	–
	Totals, Priority 2		670	570	545	470	470	2,725	

TABLE VIII-4. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
3	VIII-1 Experimental and Theoretical Investigations of the **Interactions and Coupling of the N_2-O_2 System with Other Reactions** and Species in Combustion Systems	X	200	200	200	200	200	1,000	100/yr
3	VIII-4 Experimental Determination of the **Global Kinetics of Dilute HC-O_2 Systems** and **Kinetics in Quenched Systems**	–	100	100	100	100	–	400	–
3	VIII-10 Experimental and Theoretical Studies of the **Kinetics and Mechanism of HC Pyrolysis** Reactions	X	50	50	50	50	50	250	50/yr
3	VIII-12 Experimental Studies of the **Formation and Destruction of PNA** in flames	X	100	100	100	100	100	500	–
3	VIII-13 Experimental and Theoretical Investigations of the **Formation of Soot in Flames**	X	75	75	75	75	75	375	150
3	VIII-19 Experimental Studies of Single or Small Number of **Burning Droplets and Particles** to Determine the Relation of Size and Other Factors to Pollutant Formation	X	100	75	75	75	–	325	–
	Totals, Priority 3		625	600	600	600	425	2,850	

TABLE VIII-4. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
4	VIII-5 Experimental Investigation of **Wall-Quenching Phenomena** as Related to the Formation of Pollutants	–	85	200	150	150	150	735	–
4	VIII-6 Experimental Investigation of the **Kinetics of Oxygenated Intermediates** and Their **Destruction by Oxidation**	–	50	50	50	–	–	150	–
4	VIII-7 Experimental Investigation of the **Contribution of Specific Fuel Constituents to Odor Production** in the Combustion Process	X	50	50	50	–	–	150	–
4	VIII-14 Investigations of the **Kinetics** and **Mechanism of Soot Combustion in Flames** and Post-Combustion Gas Streams	X	100	100	100	100	100	500	–
4	VIII-26 Experimental Determination of the Relation of Pollutant Output to **Path History Along Flow Paths Typical of Combustion Systems Burning Vaporized Hydrocarbons** at Pressures Other Than Atmospheric	X	250	175	175	100	100	800	–
	Totals, Priority 4		535	575	525	350	350	2,335	

TABLE VIII-4. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000						
			By Fiscal Years					5-Year Total	On-Going '76+
			'71	'72	'73	'74	'75		
5	VIII-2 Experimental Studies of the **Contribution of Combined Nitrogen in Fuels** to the Emission of NO_X	–	100	100	75	50	50	375	–
5	VIII-9 Fundamental Experimental Studies of **HC Oxidation Kinetics**	–	50	50	50	50	50	250	50/yr
5	VIII-11 Experimental Investigation of the Contribution of **PNA Contained in Solid and Liquid Fuels** to the Emission of **PNA**	–	50	50	–	–	–	100	–
5	VIII-15 Analytical and Experimental Studies of the **Kinetics of Sulfur Oxidation** in the Combustion Process	X	75	75	–	–	–	150	–
5	VIII-17 Analytical and Experimental Investigation of the Influence of **Inhomogenieties** on Pollutant Formation in **Droplet Flames** and **Pulverized-Coal Flames**	–	75	75	–	–	–	150	–
5	VIII-21 Experimental Determination of the **Effect of Composition Gradients and Gaseous Fuel Type** on the Production of Pollutants in **Laminar Diffusion Flames**	X	90	60	60	60	–	270	–
5	VIII-23 Experimental Determination of the **Effect of Pressure** on Pollutant Formation **in Laminar Diffusion Flames**	–	100	75	75	–	–	250	–
5	VIII-24 Experimental Investigation of the **Effect of Pressure** on Pollutant Formation in **Turbulent Diffusion Flames**	–	200	150	150	–	–	500	–
	Totals, Priority 5		740	635	410	160	100	2,045	

TABLE VIII-4. (Continued)

Relative Priority Rating	R&D Opportunity		Current NAPCA R&D Effort	Estimated R&D Costs, $1000						
				By Fiscal Years					5-Year Total	On-Going '76+
				'71	'72	'73	'74	'75		
N	VIII-N	Provision for Exploring New Concepts and New Research Opportunities that Evolve from the Program and Accelerating Promising Fundamental and Broadly Applicable Combustion Research that Promises to Yield Insight or to Solve Problems Associated with Applied Research	–	–	150	200	250	300	900	–
		Total, All Priorities		3,370	3,205	2,855	2,405	2,220	14,055	

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Chapter IX

SUMMARY OF THE 5-YEAR COMBUSTION R&D PLAN

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CHAPTER IX

SUMMARY OF THE 5-YEAR COMBUSTION R&D PLAN

SCOPE OF CHAPTER

This summary chapter includes discussion of several features of the Plan which should be recognized to provide a proper perspective for its utilization. In addition, recommendations are presented for supporting activities needed to enhance implementation of the R&D results growing out of the program. Finally, summary tables are provided showing funding levels for the Plan – by year, by 5-year total, by priorities, and by program elements.

COMMENTS ON FEATURES AFFECTING UTILIZATION OF THE PLAN

Several aspects of the Plan which should be recognized in its utilization relate to (1) the limitations of scope of the Plan, (2) the organization of the Plan, including the historic problem of allocating resources between application-oriented R&D and fundamentally oriented research, (3) presentation of competing research opportunities, and (4) provision for adding new R&D on new concepts not now identified or for accelerating on-going R&D.

1. Scope Limitation of the Plan

It should be reemphasized that the plan considers only research concerned with combustion modification in energy-conversion combustion processes which use prime fuels. Other combustion processes, and combustion processes not using prime fuels, are not considered, nor are the research needs of other approaches to emission control considered. Also, the scope of the plan does not include research activities which are not directly concerned with the combustion process, even though such activities may be necessary for the successful implementation of some included combustion research.

Thus, the Plan represents only a part of the total R&D activities which can be directed towards a reduction of air pollution from combustion sources. Plans in these other areas must obviously be considered together with this Combustion Plan in developing a coordinated research and development program.

2. Organization of the Plan and Allocations Between Fundamental and Applied Areas

Program elements of the Combustion R&D Plan correspond to the scope outlined in each of the previous chapters, generally organized by applications or source categories, namely:

- **Central-Station Power Plants**
- **Industrial Processing**
- **Industrial Steam Generation and Commercial and Residential Heating**
- **Continuous-Combustion Engines –**
  Gas Turbines and External-Combustion Engines
- **Reciprocating IC Engines**
- **Fundamental and Broadly Applicable Combustion Research.**

Although these program elements do not correspond directly to the organization of APCO, it is believed that this selection of program elements, by grouping like applications and considering all pertinent pollutants within these applications, is best suited to the development and presentation of this Plan.

R&D opportunities have been recommended and priorities ranked within each of these elements. The lack of short-range benefit that could be attributed to fundamental research precluded development of a common ranking scale based on benefit for the fundamental and applied-R&D areas. Therefore, the research opportunities in the fundamental and broadly applicable area have been priority ranked according to their relevance to applied-R&D needs. Thus, although the ranking procedure is different from that used to rank the applied-R&D opportunities, the two sets of priority rankings do provide a device for allocating research resources between the two areas. Judgmental criteria may still be applied to include other factors.

3. Competing Research Opportunities

Another aspect which may require consideration is that this Plan does not distinguish between parallel or competing research opportunities in the same area, other than through the priority ranking procedure. This is not a limitation if adequate funding is available and allows for parallel approaches where desirable, particularly early in the program. As research progresses and the factors entering the ranking process become better defined, application of the planning methodology will select the more favorable line. However, in the event of restrictive funding levels, it may be necessary to make additional judgmental decisions between competing research opportunities.

4. Provisions for Exploring New Opportunities and Accelerating Promising Research

In planning for future R&D, it is not possible to anticipate every need or include every possible research opportunity of merit. To provide for the funding of promising new research opportunities, as well as to possibly accelerate other work along promising lines, an unranked "research opportunity" has been added to each of the program elements and coded *New Concepts (N)* for the tabulations.

The funding level associated with each of these unranked new-concept provisions was established judgmentally by considering the importance of the respective program elements, the likelihood that new, high priority, research opportunities might be conceived within that element, and the likely relative funding level of that element. The resulting total unranked funding level is approximately 20 percent of the total *A* + *B* priority funding in the application-oriented areas, and 15 percent of the *1* + *2* priority funding in the fundamentally oriented area.

It should be noted that the funding explicitly associated with these unranked R&D opportunities represents only a part of the funds that would be anticipated to be available for such purposes. As a result of the dynamic characteristics of the Plan, some lines of investigation undertaken will undoubtedly be abandoned as research results refine the basis for the benefit calculation. It is assumed here that unexpended funds originally committed to such investigations become a part of the unranked funding and, thus, become available for contingency purposes.

SUPPORTING ACTIVITIES

In addition to the specific R&D in technical areas, supporting activity is recommended to (1) coordinate related R&D and communicate the results of the combustion-R&D program to engineering designers as a means of expediting control implementation by combustion modification, and (2) provide for periodic updating of the Combustion R&D Plan. Provision for these activities is included in the summary tables of program funding.

1. Coordination and Communication

The following activities are needed to obtain maximum effectiveness of the resources allocated for the Combustion R&D Plan:

- To monitor air-pollution-related and potentially useful combustion R&D by all sectors:
  - APCO R&D
  - Other government R&D
  - Trade associations
  - Private industry (when reported).
- To collect, update, and distribute bibliographies on pertinent subjects (with significant abstracts) to stimulate interchange of ideas.
- To provide for interpretation of fundamental research results for use by designers in engineering application. (The preparation of comprehensive monographs in specific areas could serve as a vehicle to speed utilization of fundamental research results in other R&D programs and in control implementation.)
- To sponsor or organize technical conferences of specific scope, with prompt and broad publication of proceedings or notes:
  - Small conferences of R&D personnel
  - Open conferences.

- To speed and broaden report distribution of APCO-supported R&D
  - Contracts
  - In-house R&D
  - Grants.

The current practice for handling APCO contract reports is through the National Technical Information Service, with announcement of availability and distribution of xerocopies to requesters, usually a number of months after the report is issued. (No similar procedure appears standardized as yet for reporting results of in-house or grants research.) An additional procedure is recommended whereby R&D organizations having a special interest in a given area could be placed on a distribution list to automatically receive copies of reports in that area as soon as issued.

2. Future Program Planning

The supporting activity for the R&D program should provide for periodic updating of the opportunities and priorities. The overall planning rationale and the methodology of priority ranking of R&D opportunities, as described in Appendix A, permits iteration of the technique to reflect new technology and new criteria.

SUMMARY TABLES OF R&D AND FUNDING LEVELS FOR THE 5-YEAR PLAN

The following tables summarize the R&D opportunities and funding requirements of 5-Year Combustion R&D Plan:

Table IX-1. Summary of R&D Opportunities and Funding Levels by Priorities

Listing all applied R&D opportunities, grouped by priorities, with estimated annual funding. (Funding for each priority in the fundamental category is also shown.)*

Table IX-2. Summary of Funding Levels by Program Elements**

Listing of estimated annual funding by program element and by priorities within each element.

Table IX-3. Summary of 5-Year Funding by Cumulative Priorities**

Listing of estimated 5-Year funding by accumulating highest priority categories for each program element.

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*Total funding levels for opportunities in each of the five priority categories of fundamental and broadly applicable research are included at the end of each of the corresponding applied R&D priority categories.

**Tables IX-2 and IX-3 are also included at the end of the Executive Summary as Tables I-2 and I-3 respectively.

TABLE IX-1. SUMMARY OF R&D OPPORTUNITIES AND FUNDING LEVELS BY PRIORITIES FOR 5-YEAR COMBUSTION R&D PLAN

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
A	III-6	Experimental Investigation of the **Combustion Mechanism of Coal in a Fluidized Bed** of Noncombustible Particles	X	125	125	250	–	–	500
A	III-7	Experimental Investigation of Factors Influencing **Completeness of Coal Combustion in Fluidized Beds with Low Excess Air**	X	50	75	125	250	–	500
A	III-8	Development of Improved **Coal Gasification Systems** to Produce Sulfur- and Ash-Free Gas Suitable for **Advanced Power Cycles**	X	100	125	150	300	325	1,000
A	VI-4	Development of a Low-Emission **Automotive-Size Gas-Turbine Combustor** Prototype	–	200	200	200	200	–	800
A	VI-5	Development of Low-Emission **Combustors for Rankine-Cycle** Automotive Engines	X	500	300	200	200	–	1,200
A	VII-1	Support of Development and Evaluation of **Stratified-Charge** Gasoline Engines	X	400	400	400	–	–	1,200
A	VII-2	Development of Implementation Criteria for **Lean-Mixture Operation of Gasoline Engines**	X	200	260	200	–	–	660
A	VII-3	Experimental Research on the Effect of **Fuel-Air Mixture Preparation** on Gasoline-Engine Emissions	X	100	100	100	–	–	300
		Totals, Priority A		1,675	1,585	1,625	950	325	6,160

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
1	VIII	All Priority 1 Fundamental and Broadly Applicable Combustion Research	–	800	675	575	575	575	3,200
B	III-2	Analytical and Experimental Research to Develop Criteria for the Application of **Flue-Gas Recirculation** to **Minimize NO_X** Emission from Central-Station Power Plants	X	200	850	1,050	2,500	3,000	7,600*
B	III-3	Experimental Investigation to Develop Design Criteria for the Application of **Two-Stage Combustion** for NO_X Control, with Demonstration in a Coal-Fired Central-Station Power Plant	X	200	200	400	400	1,000	2,200*
B	III-4	Experimental Investigation to Develop Design Criteria for the Application of **Two-Stage Combustion** for NO_X Control, with Demonstration in an Oil-Fired Central-Station Power Plant	X	200	300	300	1,000	–	1,800*
B	III-14	Analytical and Experimental Investigation of the **Feasibility of Fluxing Coal Ash** for Minimizing Emission of Particulates from Central-Station Power Plants	–	100	100	100	–	–	300
B	V-1	Experimental Investigation to Develop **Design Criteria** for Minimum Pollutant Emissions from Small- and Intermediate-Size Combustion Equipment, Considering **Mixing, Turbulence, Combustion Intensity, and Furnace Temperature**	X	200	200	150	150	150	850
B	V-2	Experimental Laboratory Investigation of the Effect of **Internal Recirculation** on Emissions, Demonstration of Optimum Internal Recirculation on Several Small- and Intermediate-Size Combustion Units, and Development of **Design Criteria**	–	100	150	200	200	100	750
B	V-3	Development of **Analytical Models to Provide Design Guidance** for Small- and Intermediate-Size Combustion Equipment	–	75	75	125	125	100	500

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000					
			By Fiscal Years					5-Year Total
			'71	'72	'73	'74	'75	
B	VI-3 Analytical and Experimental Research to Develop **Criteria for Reduction of CO, HC, and Odor** Emissions From Aircraft Gas Turbines at **Idle** and **Low Power**	–	250	200	200	–	–	650
B	VII-7 Initiate Development of a **Model of the Diesel-Engine Combustion Process** by Analytical and Experimental Development of a **Fuel-Air Mixing-and-Vaporization Model**	X	200	200	200	200	200	1,000
B	VII-8 Experimental Investigation to **Identify Odor-Producing Constituents** in **Diesel-Engine Exhaust**, the **Mechanism of their Formation** and Combustion Modifications to Reduce Emissions of the Constituents	X	100	100	100	100	100	500
B	VII-9 Experimental Laboratory Research on **Pre-Flame and Non-Flame Reactions** in Diesel-Engine Combustion	–	70	70	70	70	70	350
	Totals, Priority B		1,695	2,445	2,895	4,745	4,720	16,500
2	VIII All Priority 2 Fundamental and Broadly Applicable Fundamental Combustion Research	–	670	570	545	470	470	2,725
C	III-12 Experimental Investigation of the Effect of **Mineral Composition of Coal on Fly-Ash Resistivity** and Other Characteristics	X	75	75	125	–	–	275
C	III-13 Analytical and Experimental Investigation of the **Effect of Combustion Conditions on Fly-Ash Resistivity** and Other Characteristics	X	50	100	150	150	–	450
C	III-15 Analytical and Experimental Investigation of a **Super-Slagging Furnace** to Achieve High **Capture of Coal Ash** for Central-Station Power Plants	–	100	150	150	300	400	1,100

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
C	III-16	Development of Improved **Research Instrumentation** and Sampling for Measurement of Local Conditions **Within Combustion Systems**	–	100	150	150	100	–	500
C	V-5	Experimental Investigation of the Mechanisms by which PNA is Formed and Destroyed during the Combustion of Coal on **Fixed Beds** and Development of **Design Criteria to Minimize PNA** Emissions with Demonstrations on Boiler Units	X	150	150	150	150	–	600
C	V-7	Experimental Investigation of the Application of **Flue-Gas Recirculation** and **2-Stage Combustion** (and in combination) to Typical Oil- and Gas-Fired Industrial **Package Boilers** with One Demonstration Prototype	X	250	200	200	–	–	650
C	V-10	Experimental Investigation to Develop **Low-Peak-Temperature Residential Heating Units to Reduce NO_X** Emissions	–	75	100	150	150	–	475
C	V-13	Measurement of Emissions from Various Types of Industrial, Commercial, and Residential Combustion Equipment to Develop **More Comprehensive Emission Factors** and to **Provide Design Guidance**	X	150	150	60	60	60	480
C	VI-1	Analytical and Experimental Research on Relation of **Gas-Turbine Combustor Primary-Zone Design** to Emission of NO_X	X	200	200	–	–	–	400
C	VII-4	Analytical and Experimental Research on **Gasoline-Engine Wall-Quench Phenomena**	–	100	100	100	–	–	300
		Totals, Priority C		1,250	1,375	1,235	910	460	5,230
3	VIII	All Priority 3 Fundamental and Broadly Applicable Combustion Research	–	625	600	600	600	425	2,850

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
D	III-1	Experimental Investigation of Feasibility of **Burning Pulverized Coal with Low Excess Air**	–	125	125	250	–	–	500
D	III-5	Exploratory Research and Experimental Feasibility Evaluation of a Low-Emission **Combustion System** for Central-Station Power Plants using the Concept of a **High-Turbulence Primary Combustion Zone Plus a Plug-Flow Zone**	–	100	150	150	250	300	950
D	III-10	Laboratory-Scale and Field Investigation of the **Effect of Rank of Coal on Emission of NO_X**	–	75	75	–	–	–	150
D	V-6	Experimental Investigation of the Application of **Flue-Gas Recirculation** and **2-Stage Combustion** (and in combination) to **Residential and Small-Commercial Oil & Gas Burners** with Demonstration Prototypes	X	200	200	200	–	–	600
D	V-9	Conceptual Design and Supporting Experimental Investigations to Guide the Application of **Fluidized-Bed Combustion** of Coal to **Industrial Steam Generation**	X	250	250	250	150	150	1,050
D	V-11	Experimental Investigation of **Additives and Emulsions** for Reducing Emissions from **Residual Fuel-Oil** Combustion	X	100	75	–	–	–	175
D	V-12	Experimental Investigation of the Effect of Burner **Maintenance** on Emissions from Commercial and Residential Oil Burners and Development of **Design Criteria to Minimize Performance Deterioration**	–	150	75	75	–	–	300

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
D	VI-2	Analytical and Experimental Research to Explore Relation of **Gas-Turbine Secondary-Combustion- and Dilution-Zone Design** to NO_x Emission	–	100	200	200	–	–	500
D	VII-5	Experimental Research on the **Effect of Lubricating Oil** on Gasoline-Engines Emissions	–	70	70	70	–	–	210
D	VII-6	Experimental Research on the **Formation of Particulate and PNA** Emissions from Gasoline Engines	X	200	200	200	200	200	1,000
D	VII-10	Investigation of **Kinetics of Nitrogen-Oxide Formation** in IC engines with **Fuel-Rich Mixtures**	X	100	100	–	–	–	200
		Totals, Priority D		1,470	1,520	1,395	600	650	5,635
4	VIII	All Priority 4 Fundamental and Broadly Applicable Combustion Research	–	535	575	525	350	350	2,335
E	III-9	Exploration of the Feasibility of **Electrochemical Oxidation of Coal** for Direct-Energy Conversion	–	100	100	100	100	100	500
E	III-11	Laboratory-Scale Investigation of the **Effect of Residual Fuel-Oil Properties and Composition** on Emissions, and Development of Convenient **Methods to Characterize Oils** in Terms of Emission Tendency, Including NO_x and Particulates	–	125	150	200	–	–	475
E	IV-1	Analytical and Experimental Research on the Reduction by Combustion Modifications of **NO_x from Rotary Kilns** for Production of Cement and Lime, Including Full-Scale Demonstration Application	–	100	200	200	200	–	700*

TABLE IX-1. (Continued)

Relative Priority Rating		R&D Opportunity	Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
E	IV-2	Analytical and Experimental Research on the Reduction of **NO_x from Glass Melting Furnaces** by Combustion Modifications	–	100	200	100	–	–	400
E	IV-3	Analytical and Experimental Research on Reduction of **NO_x Emissions from Open-Hearth Furnaces** by Modifications of Firing Techniques, Including Demonstration	–	250	250	500	1,000	–	2,000*
E	IV-4	Analytical and Experimental Investigation of Fuel-Rich Afterburning to Reduce **NO_x Emission from Regenerative Melting Furnace**	X	100	300	300	100	–	800*
E	IV-5	Analytical and Experimental Investigation of Combustion Modifications to Reduce **NO_x Emission from Iron-Sintering and Iron-Pelletizing Processes**	–	100	200	–	–	–	300
E	V-4	Experimental Investigation of the Contribution of **Transient Conditions** to Emissions from Residential and Small Commercial Combustion Equipment, and Development of Means of Minimizing Emissions During Transient Conditions	X	200	175	150	125	125	775
E	V-8	Experimental Laboratory Investigation of the Application of **Flue-Gas Recirculation** to **Fixed-Bed Coal Combustion** with Laboratory Demonstration	–	200	300	300	300	–	1,100
		Totals, Priority E		1,275	1,875	1,850	1,825	225	7,050
5	VIII	All Priority 5 Fundamental and Broadly Applicable Combustion Research	–	740	635	410	160	100	2,045

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
N	III-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations** of Promising Concepts for Reducing Emissions from Central-Station Power Plants by Combustion Modification	–	–	250	350	400	500	1,500
N	IV-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Combustion Equipment used for Industrial Processing by Combustion Modification	–	–	50	50	50	50	200
N	V-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Combustion Equipment used for Industrial Steam Generation and for Space and Water Heating by Combustion Modification	–	–	150	200	250	250	850
N	VI-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations** of Promising Concepts for Reducing Emissions from Gas Turbines and External Combustion Engines by Combustion Modification	–	–	100	150	150	200	600

TABLE IX-1. (Continued)

Relative Priority Rating	R&D Opportunity		Current APCO R&D Effort	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
N	VII-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program, **Accelerating Promising R&D**, or **Conducting Demonstrations of Promising Concepts** for Reducing Emissions from Reciprocating Internal-Combustion Modification	–	–	250	300	300	350	1,200
N	VIII-N	Provision for Exploring **New Concepts and New R&D Opportunities** that Evolve from the Program and **Accelerating Fundamental and Broadly Applicable Combustion Research** that Promises to Yield Insight or to Solve Problems Associated with Applied Research	–	–	150	200	250	300	900
		Totals, Priority N		0	950	1,250	1,400	1,650	5,250
–	–	**Communications and Planning**	–	300	300	300	300	300	1,500
		Totals, All Applied R&D		7,365	9,600	10,050	10,180	7,730	44,925
		Totals, All Fundamental Research		3,370	3,205	2,855	2,405	2,220	14,055
		Totals, All R&D		11,035	13,105	13,205	12,885	10,250	60,480

TABLE IX-2. SUMMARY OF FUNDING LEVELS BY PROGRAM ELEMENTS AND PRIORITIES FOR 5-YEAR COMBUSTION R&D PLAN

R&D Described in Chapter	Program Element or Source Category	Priority Level	Number of R&D Opportunities	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
III	Central-Station Power Plants	A	3	275	325	525	550	325	2,000
		B	4	700	1,450	1,850	3,900	4,000	11,900
		C	4	325	475	575	550	400	2,325
		D	3	300	350	400	250	300	1,600
		E	2	225	250	300	100	100	975
		N	1	–	250	350	400	500	1,500
		Total	**17**	**1,825**	**3,100**	**4,000**	**5,750**	**5,625**	**20,300**
IV	Industrial Processing	A	0	–	–	–	–	–	–
		B	0	–	–	–	–	–	–
		C	0	–	–	–	–	–	–
		D	0	–	–	–	–	–	–
		E	5	650	1,150	1,100	1,300	–	4,200
		N	1	–	50	50	50	50	200
		Total	**6**	**650**	**1,200**	**1,150**	**1,350**	**50**	**4,400**
V	Industrial Steam Generation and Commercial and Residential Heating	A	0	–	–	–	–	–	–
		B	3	375	425	475	475	350	2,100
		C	4	625	600	560	360	60	2,205
		D	4	700	600	525	150	150	2,125
		E	2	400	475	450	425	125	1,875
		N	1	–	150	200	250	250	850
		Total	**14**	**2,100**	**2,250**	**2,210**	**1,660**	**935**	**9,155**

TABLE IX-2. (Continued)

R&D Described in Chapter	Program Element or Source Category	Priority Level	Number of R&D Opportunities	Estimated R&D Costs, $1000					
				By Fiscal Years					5-Year Total
				'71	'72	'73	'74	'75	
VI	Continuous Combustion Engines – Gas Turbines and External-Combustion Engines	A	2	700	500	400	400	–	2,000
		B	1	250	200	200	–	–	650
		C	1	200	200	–	–	–	400
		D	1	100	200	200	–	–	500
		E	0	–	–	–	–	–	–
		N	1	–	100	150	150	200	600
		Total	**6**	**1,250**	**1,200**	**950**	**550**	**200**	**4,150**
VII	Reciprocating Internal-Combustion Engines	A	3	700	760	700	–	–	2,160
		B	3	370	370	370	370	370	1.850
		C	1	100	100	100	–	–	300
		D	3	370	370	270	200	200	1,410
		E	0	–	–	–	–	–	–
		N	1	–	250	300	300	350	1,200
		Total	**11**	**1,540**	**1,850**	**1,740**	**870**	**920**	**6,920**
VIII	Fundamental and Broadly Applicable Combustion Research	1	4	800	675	575	575	575	3,200
		2	4	670	570	545	470	470	2,725
		3	6	625	600	600	600	425	2,850
		4	5	535	575	525	350	350	2,335
		5	8	740	635	410	160	100	2,045
		N	1	–	150	200	250	300	900
		Total	**28**	**3,370**	**3,205**	**2,855**	**2,405**	**2,220**	**14,055**
	Communications and Planning			300	300	300	300	300	1,500
Overall Totals				**11,035**	**13,105**	**13,205**	**12,885**	**10,250**	**60,480**

TABLE IX-3. SUMMARY OF 5-YEAR FUNDING ESTIMATES BY CUMULATIVE PRIORITIES FOR PROGRAM ELEMENTS OF THE 5-YEAR COMBUSTION R&D PLAN

		Estimated 5-Year R&D Costs, $1,000* *(Number of R&D opportunities is shown in parentheses)*						
		Priority or Cumulative Priorities						**All Priorities**
	Applied R&D	A	A-B	A-C	A-D	A-E	N	
Chapter								
III	**Central-Station Power Plants**	2,000 *(3)*	13,900 *(7)*	16,225 *(11)*	17,825 *(14)*	18,800 *(16)*	1,500 *(1)*	20,300 *(17)*
IV	**Industrial Processing**	–	–	–	–	4,200 *(5)*	200 *(1)*	4,400 *(6)*
V	**Ind. Steam Generation & Comm. & Res. Heating**	–	2,100 *(3)*	4,305 *(7)*	6,430 *(11)*	8,305 *(13)*	850 *(1)*	9,155 *(14)*
VI	**Continuous Combustion Engines**	2,000 *(2)*	2,650 *(3)*	3,050 *(4)*	3,550 *(5)*	3,550 *(5)*	600 *(1)*	4,150 *(6)*
VII	**Reciprocating IC Engines**	2,160 *(3)*	4,010 *(6)*	4,310 *(7)*	5,720 *(10)*	5,720 *(10)*	1,200 *(1)*	6,920 *(11)*
	Totals, Applied R&D	6,160 *(8)*	22,660 *(19)*	27,890 *(29)*	33,525 *(40)*	40,575 *(49)*	4,350 *(5)*	**44,925** *(54)*
		1	1-2	1-3	1-4	1-5	N	
VIII	**Fundamental Research**	3,200 *(4)*	5,925 *(8)*	8,775 *(14)*	11,110 *(19)*	13,155 *(27)*	900 *(1)*	**14,055** *(28)*
		A and 1	A-B and 1-2	A-C and 1-3	A-D and 1-4	A-E and 1-5	N	
	Totals by Funding Levels[(a)]	**10,860**	**30,085**	**38,165**	**46,135**	**55,230**	**5,250**	**60,480**

N Indicates unranked general provision for new concepts and opportunities.

(a) Totals of applied R&D and fundamental research in priorities shown, including supporting activities of communications and planning.

*Breakdowns of recommended funding by years (FY '71-'75) are shown in individual chapters and summarized in Chapter IX. (Tables IX-1 and IX-2).

Appendix A

PRIORITY RATING METHODOLOGY FOR APPLIED-R&D OPPORTUNITIES

Joseph A. Hoess
Edgar S. Cheaney

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APPENDIX A

PRIORITY RATING METHODOLOGY FOR APPLIED-R&D OPPORTUNITIES

This appendix outlines the methodology used to establish priorities for the applied-R&D opportunities in the 5-Year R&D Plan for reduction of emissions from energy-conversion combustion (ECC) sources by combustion-process modification. Priorities were assigned on the basis of:

- Relative potential for air-pollution reduction
- Relative cost to implement the results of the research
- Expert judgment.

Specific influences or factors considered in setting priorities are discussed in the following paragraphs. These are:*

1. Pollutant-Significance Factor, P_i
2. Pollutant-Source Factor, S_{ij}

   Percent of pollutant *i* emission from all ECC sources from 1970 to 1990 contributed by ECC source *j*
3. Pollutant-Source Factor Corrected for Implementation Time, $(ST)_{ijk}$
4. Pollutant-Reduction Factor, R_{ijk}
5. Alternative-Control Factor, A_{ij}
6. Relative Potential-Benefit Factor, B_k

   Factors 1-5 are combined to give B_k:

   $$B_k = 100 \sum_{ij} P_i \times (ST)_{ijk} \times R_{ijk} \times (1-A_{ij})$$
7. Estimated increase or decrease in annual cost associated with implementation
8. Relative priority (considering Factors 6 and 7).

---

*Subscripts: *i* refers to a specific pollutant
j refers to a specific pollutant source
k refers to a specific R&D opportunity.

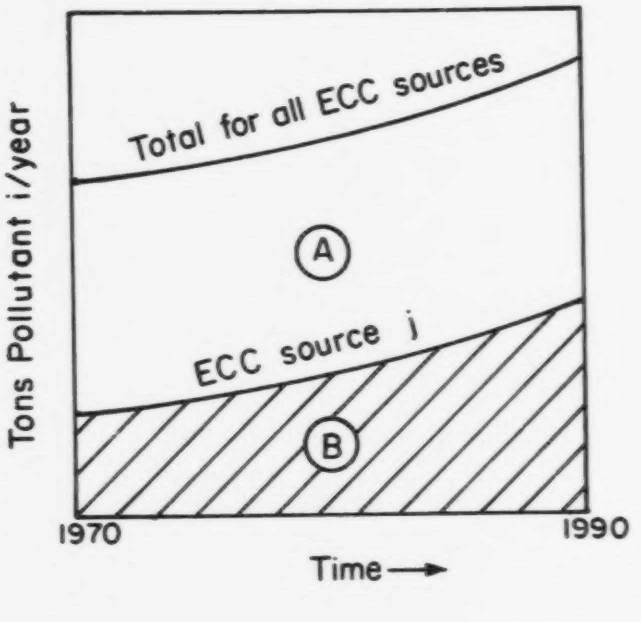
1. Pollutant-Significance Factor, P_i

The numerical value assigned to P_i for pollutant *i* is defined as the relative benefit associated with a 100 percent reduction in the projected uncontrolled emission* of pollutant *i* from all ECC sources during the period 1970 to 1990 as compared with the same percentage reduction for other pollutants for the same period. Thus, P_i is a proxy for the "total problem" over the next 20 years presented by any one pollutant that a given R&D opportunity might attack.

Nine specific pollutants were considered: combustible particulate, CO, gaseous HC, polynuclear aromatics, odor, NO_x, lead, SO_x, and fly ash (noncombustible particulate). As a result of discussions with NAPCA personnel, P_i was assumed to be unity for each of these pollutants. While the present state of knowledge concerning the relative significance of pollutant emissions does not fully support any assumption as to values for P_i, the above assumption is considered reasonable for the purposes of this planning study. When the state of knowledge permits a set of priorities to be established among the pollutants, new values for P_i can be assigned reflecting these, and the R&D Plan can be adjusted accordingly.

2. Pollutant-Source Factor, S_{ij}

S_{ij} is the projected percent emission of pollutant *i* from all ECC sources from 1970 to 1990 contributed by ECC source *j*. This factor is depicted in Figure A-1.



$$S_{ij} = \frac{\text{Area B}}{\text{Area (A+B)}} = \frac{\text{tons uncontrolled pollutant } i \text{ from ECC source } j \text{ (1970 to 1990)}}{\text{tons uncontrolled pollutant } i \text{ from all ECC sources (1970 to 1990)}}$$

Figure A-1. Definition of Pollutant-Source Factor, S_{ij}

---

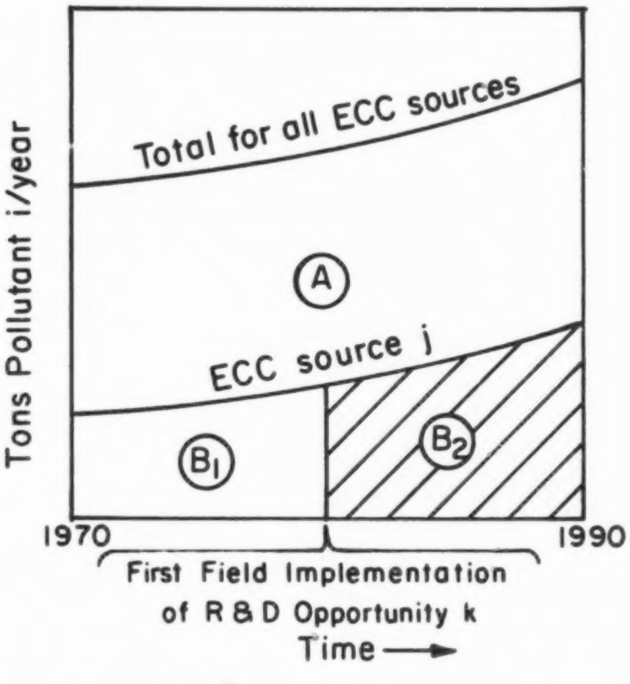
*"Projected uncontrolled emissions" are defined as the magnitude of nationwide emissions expected, without considering controls beyond existing technology. These projections are presented in Appendix B.

Table A-1 lists the values estimated for S_{ij} for each pollutant and for each source considered. Values for S_{ij} vary from 0 to 1.0, and the sum of these values for a specific pollutant for all ECC sources is equal to 1.0.

The values listed in Table A-1 were developed from the emission data and projections of emissions by sources from 1970 to 1990 which are given in Appendix B. Specifically, the values in Table A-1 can be derived from the values in Table B-5. Because there are no applicable quantitative measures or emission projections available for odor, values for S_{ij} were judgmentally assigned to this pollutant by the study team. A factor of 0.6 was assigned to diesel engines (distributed between mobile and stationary engines in the same proportion as unburned hydrocarbons) and 0.1 was assigned to aircraft gas turbines. The remaining 0.3 was distributed nonspecifically among all other ECC sources.

3. Pollutant-Source Factor Corrected for Implementation Time, $(ST)_{ijk}$

$(ST)_{ijk}$ represents the maximum percent of pollutant *i* projected between 1970 and 1990 from all ECC sources that is susceptible to reduction by the successful implementation of R&D opportunity *k* as applied to source *j*. This is depicted in Figure A-2.


Tons Pollutant i/year
Total for all ECC sources
A
ECC source j
B1
B2
1970
1990
First Field Implementation of R & D Opportunity k
Time

$$(ST)_{ijk} = \frac{\text{Area } B_2}{\text{Area } (A + B_1 + B_2)}$$

$$= \frac{\text{tons uncontrolled pollutant } i \text{ from ECC source } j \text{ from time of first operational device utilizing results of R\&D opportunity } k \text{ to 1990}}{\text{tons uncontrolled pollutant } i \text{ from all ECC combustion sources (1970 to 1990)}}$$

Figure A-2. Definition of Pollutant-Source Factor Corrected for Implementation Time, $(ST)_{ijk}$

TABLE A-1. ESTIMATED VALUES FOR POLLUTANT-SOURCE FACTOR, S_{ij}, × 10^2

(Percent of 1970-1990 Pollutant Emissions From All ECC Sources Contributed by Specific Sources)

Pollutants	Continuous Combustion for Energy Conversion												Cyclic Combustion for Energy Conversion				
	Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. Products of Incomplete Combustion																	
Combustible Particulate	19.0	0.7	0.7	8.9	18.1	1.7	3.3	2.0	4.3	3.4	2.2	1.6	17.7	9.5	0.7	6.4	n
CO	0.3	n	n	0.1	0.2	<.1	<.1	0.6	0.1	<.1	0.3	1.3	90.0	0.6	4.6	0.3	1.2
HC	0.5	0.1	n	–	0.6	0.1	0.2	0.6	0.4	n	0.5	2.5	80.8	6.8	2.0	2.0	3.0
PNA	n	n	n	6.8	n	n	n	73.1	2.1	3.9	n	n	14.0	n	n	n	n
Odor*	a	a	a	a	a	a	a	a	a	a	a	10	a	46	a	14	a
2. NO_x	20.9	2.1	3.7	2.3	3.1	1.5	2.9	0.1	2.5	2.0	2.2	1.5	41.6	3.5	0.6	1.1	8.3
3. Combustion-Improving Additives																	
Lead	n	n	n	n	n	n	n	n	n	n	n	n	99.6	n	0.3	n	n
4. Fuel Contaminants																	
SO_x	77.1	5.7	n	2.9	7.3	1.9	n	1.0	2.1	n	0.5	0.3	0.8	0.3	n	n	n
Ash	81.1	0.2	n	15.0	10.7	0.5	n	1.2	1.5	n	n	n	n	n	n	n	n

n, emission considered negligible.

*Odor source factors judgmentally assigned by Battelle staff.

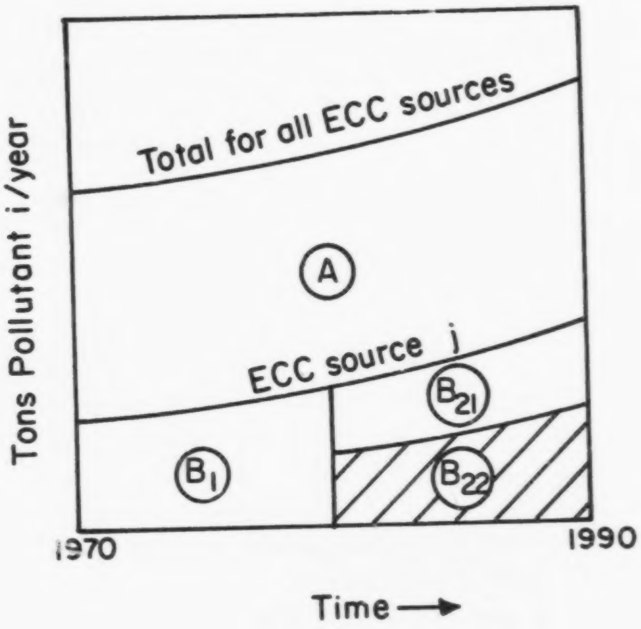
a. Remaining 30 percent of odor emissions distributed nonspecifically among these categories.

When a timing factor is applied in the above manner, an R&D opportunity estimated to require a long period before field implementation will be penalized relative to an R&D opportunity for which only a short period is required. Further, the penalty will be greater when the emission of pollutant *i* is decreasing over time than when it is increasing. For example, if the emission per year of pollutant *i* from source *j* is remaining constant over time, a maximum of 50 percent of the 1970-1990 emission of pollutant *i* from source *j* would be susceptible to reduction by an R&D opportunity to be implemented in 1980. However, if the emission of pollutant *i* were doubling every 10 years, a maximum of 67 percent of the emission would be susceptible to reduction.

In evaluating an R&D opportunity, the sum of $(ST)_{ijk}$ for each source is calculated for each pollutant affected. The results of these calculations are listed in the evaluation summaries at the end of each applied R&D opportunity description under the title, "Fraction of ECC Emissions Affected".

4. Pollutant-Reduction Factor, R_{ijk}

R_{ijk} is defined as the percent reduction of pollutant *i* from source *j* that is expected to result from completing the work recommended for R&D opportunity *k*, plus application to all systems of the sources affected. R_{ijk} is depicted in Figure A-3.



$$R_{ijk} = \frac{\text{Area } B_{22}}{\text{Area } (B_{21} + B_{22})}$$

$$(ST)_{ijk} \times R_{ijk} = \frac{\text{Area } B_{22}}{\text{Area } (A + B_1 + B_{21} + B_{22})}$$

Figure A-3. Definition of Pollutant-Reduction Factor, R_{ijk}

In establishing an average or *expected* value for R_{ijk}, the study team estimated both minimum (pessimistic) and maximum (optimistic) reductions that might result from the research and the implementation of results. They also estimated the reduction that in their opinion is most likely to result, taking into account the technical feasibility of the particular R&D opportunity in question. On the basis of the assumption that the underlying probability distribution for the reduction factors follows a Beta distribution, the expected value (at this point in time) of the reduction factor can be estimated by:

$$\textit{expected}\text{ reduction} = 1/6\ [\text{pessimistic estimate} + 4\ (\text{most likely estimate}) + \text{optimistic estimate}].$$

Both the estimated range of values and calculated expected values for R_{ijk} are listed in the evaluation summaries. The expected value is used in the calculation of B_k.

5. Alternative-Control Factor, A_{ij}

A_{ij} is a judgmental factor which allows for the likelihood that competing noncombustion controls (e.g., downstream controls) may be applied to remove a specific pollutant from a given source. A_{ij} is applied to reduce the relative benefit associated with R&D opportunities which are applicable to the particular pollutants and sources in question. A_{ij} is applied by multiplying the product of the Pollutant-Source Factor Corrected for Implementation Time and Pollutant-Reduction Factor by $(1-A_{ij})$.

Table A-2 is a listing of the values assigned to A_{ij} for various combinations of sources and pollutants. (Except for coal-fired boilers and reciprocating internal-combustion engines, noncombustion controls were not considered likely to significantly reduce emissions and, therefore, A_{ij} was assigned a value of zero for all pollutants.)

Values for A_{ij} are listed in the evaluation summaries for the R&D opportunities under the title "Noncombustion-Controls Factor". Where an R&D opportunity is applicable to more than one source, a composite value is listed. The composite value is the weighted average of the value of A_{ij} for each of the sources affected. The weighting is proportional to the amount of the pollutant in question contributed by each source.

Coal-Fired Power Plants and Industrial Steam Generation

Combustible particulate and ash were assigned values of 0.7 and 0.5 for coal-fired power plants and industrial steam generation, respectively, to allow for wider application and higher efficiencies from mechanical separators and electrostatic precipitators in those applications. SO_x was assigned a value of 0.3 for coal-fired power plants to allow for the possible use of the various downstream controls currently under development or in the advanced engineering stage.

Gasoline Engines

Hydrocarbons and CO can be controlled effectively by both manifold reactors and catalytic reactors. Although neither of these devices is presently available in a practical, low-cost form, no other controls appear more feasible at present. Therefore, A_{ij} for HC and CO was estimated at 0.8.

TABLE A-2. ASSIGNED VALUES FOR ALTERNATIVE-CONTROL FACTOR, A_{ij}

Pollutants	Continuous Combustion for Energy Conversion												Cyclic Combustion for Energy Conversion				
	Central Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. **Products of Incomplete Combustion**																	
Combustible Particulate	.7	0	0	–	.5	0	0	–	0	0	–	–	.5	.5	.5	.5	0
CO	0	0	0	–	0	0	0	–	0	0	–	0	.8	.5	.8	.5	0
HC	0	0	–	–	0	0	0	–	0	0	–	0	.8	.5	.8	.5	0
PNA	0	–	–	–	0	0	0	0	0	0	–	–	.4	.4	.4	.4	0
Odor	–	–	–	–	–	–	–	–	–	–	–	0	–	.5	–	.5	–
2. **NO_x**	0	0	0	0	0	0	0	–	0	0	0	0	.2	.1	.2	.1	.2
3. **Combustion-Improving Additives**																	
Lead	–	–	–	–	–	–	–	–	–	–	–	–	.8	–	.8	–	0
4. **Fuel Contaminants**																	
SO_x	.3	–	–	–	0	–	–	–	–	–	–	–	–	–	–	–	–
Ash	.7	0	0	–	.5	–	–	–	–	–	–	–	–	–	–	–	–

–, An assumed value for A_{ij} was not required for these combinations of pollutant-source classifications and pollutant categories.

Removal of NO_x presently appears more difficult than removal of CO and HC. Some experimental devices for catalytic reduction are claimed to be effective, but there have been no convincing public demonstrations. On the other hand, exhaust-gas recirculation is in the advanced experimental-development stage and promises to suppress 50 to 75 percent of the NO_x. Lean-mixture operation is another promising approach, though not as far advanced.

There is no firm basis at present for estimating A_{ij} for NO_x emissions from gasoline engines. However, since noncatalytic controls presently are preferable and somewhat more feasible, a value of 0.2 was assumed.

Lead particulates will probably be eliminated through the removal of lead additives from the fuel. Therefore, A_{ij} for lead was assumed to be 0.8. Other particulates will probably be removed by downstream cleanup devices. However, the nature of the required cleanup device will be affected by the amount, size, and composition of the particulates. Consequently, possible combustion modification to make the particulates easier to control would be worthwhile. Therefore, A_{ij} was assumed to be 0.5 for combustible particulates.

PNA emissions have been observed to be affected by fuel, lube-oil, and engine variables. PNA compounds such as benzo(a)pyrene can be present in the fuel and can be formed during the combustion process. They would probably be vaporized at exhaust temperature, but would be a liquid or solid particulate at normal ambient temperature. For the present, it appears that A_{ij} for PNA should be somewhat lower than for particulates in general. A value of 0.4 was assumed.

No noncombustion controls for gasoline-engine emissions of odor, SO_x, or ash are anticipated.

Diesel Engines

Because there is far greater latitude for modifying the diesel-engine combustion process without changing the basic nature of the engine than there is for the gasoline engine, and because diesels are not facing stringent emission controls in the very near future, generally lower values for A_{ij} were assumed for the diesels than for gasoline engines. The assumed values are listed in Table A-2.

Natural-Gas Engines

Except for NO_x, the pollutant emissions from natural-gas engines are generally quite low. Thus, no noncombustion control was assumed for these pollutants. A_{ij} for NO_x was assumed to be 0.2 to allow for the possible use of catalytic controls.

6. Potential-Benefit Factor, B_k

B_k is a single overall numerical measure of the relative benefit (i.e., percentage reduction in total ECC pollutant emissions over the 1970-1990 period) ascribed to each R&D opportunity. It is defined as the product of each of the factors discussed up to this point, summed for each pollutant and source affected:

$$B_k = 100 \sum_{ij} P_i \times (ST)_{ijk} \times R_{ijk} \times (1-A_{ij}),$$

where $(ST)_{ijk}$ and R_{ijk} are expressed as fractions. Values calculated for B_k for all the applied R&D opportunities range from 0.04 to 46.50.

7. Implementation Cost

Implementation cost for an R&D opportunity is defined as the total cost to society for implementing the results of the R&D by application to all installations within the source category affected. In general, the magnitude of the implementation cost for an R&D opportunity would far exceed the cost of performing the R&D. Consequently, implementation cost was the only cost factor considered significant in establishing priority rankings.

Estimates of implementation cost were made by the project staff on the basis of experience and analogy. These estimates were made in terms of the increase or decrease in annual (i.e., 1980) cost that might result from application of the results of the R&D opportunity to all systems of the sources affected. Considered in the estimates were:

- Changes in capital equipment depreciation and other capital charges per year. This item was estimated to be equal to 0.15 times the change in capital equipment cost.
- Changes in fuel, additive, and power costs per year.
- Changes in operating labor and maintenance costs per year.

In estimating these changes in yearly cost, no attempt was made to follow an implementation model in which yearly costs would be dependent on the timing of introduction of new systems and retrofitting of existing systems. Rather, an artificial condition was assumed where the results of the R&D were assumed to have been applied to all systems of the sources affected. Further, changes in capital-equipment cost were estimated as though the results of the R&D had been incorporated into all systems when they were new.

Because detailed cost studies were not made, and because of the uncertainty necessarily involved in making estimates for so far in the future and for items not yet developed, the estimates of implementation cost were translated into a "verbal portrayal" of the values (high, medium, low, and very low). These verbal portrayals represent the following approximate cost ranges:

High	– greater than $1 billion per year	(>$$10^9$)
Medium	– $100 million to $1 billion per year	($$10^8$ to 10^9)
Low	– $10 million to $100 million per year	($$10^7$ to 10^8)
Very low	– less than $10 million per year	(<$$10^7$)

8. Combination of Benefits and Costs for Priority Rankings

Ideally, it would be desirable to assign a unique priority index to each individual project in the total Plan (independent of program element). While such a numerical rating was utilized in the planning process, the individual ratings have been categorized for purposes of this report. The estimates and forecasts involved in the calculations of benefits and implementation costs were considered too uncertain to permit such fine discrimination in presenting the final results of the priority ranking. Instead, projects were clustered into five priority groupings: *A, B, C, D,* and *E.* The groupings have common significance for all the applied program elements since all applied-R&D opportunities in these elements were evaluated on the same basis.

In assigning R&D opportunities to one of the five priority groupings, both potential for pollution reduction (as measured by B_k) and the general magnitude of possible implementation cost (as measured by the verbal portrayals of cost) were considered. However, greater emphasis was placed on potential for air-pollution reduction than on possible implementation costs. This reasoning is based on the fact that the benefit estimates are considered more important (and more reliable) at this time than the implementation-cost estimates. Furthermore, the need for actually funding the implementation of a given project cannot possibly arise until the research is nearing completion. At that time, a far better appraisal of both costs and benefits can be made. Therefore, although implementation cost should be accounted for in establishing priority, it is logical to reduce its significance at this time compared with the significance of expected benefits.

The procedure used to accomplish the combined priority ranking was to assign a numerical value on a logarithmic scale, i.e., 1, 2, 4, and 8, to each of the four implementation cost categories, i.e., very low, low, medium, and high, respectively. The B_k for a given R&D opportunity was then divided by either 1, 2, 4, or 8, depending on the implementation cost category into which the R&D opportunity was estimated to fall. The resulting modified B_k values were then rank ordered from highest to lowest, and cutoff points were judgmentally selected to define priority groupings *A, B, C, D,* and *E.*

While the procedure does not permit the R&D opportunities rated lowest with respect to potential for pollution reduction to be ranked in the *A*-priority group, it does permit some modest variations in priority ranking due to consideration of implementation costs. For example, some R&D opportunities with medium values for B_k were ranked in either *B*-, *C*-, or *D*-priority groups, depending on whether they were estimated to have very low, low, or medium implementation costs.

Appendix B

DERIVATION OF THE EMISSION DATA AND PROJECTIONS USED IN PLANNING

Philip R. Sticksel
Richard B. Engdahl

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DEVELOPMENT OF EMISSION INVENTORY DATA IN TABLE II-1 . . . . B- 1

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Projections for Cyclic-Combustion Applications . . . . -17

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SOURCES OF PROJECTIONS FOR COMBUSTION EMISSIONS . . . . - 3

- **Projections for Continuous-Combustion Applications . . . . -10**
- **Projections for Cyclic-Combustion Applications . . . . -17**

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B. EMISSIONS PROJECTIONS

APPENDIX B

DERIVATION OF THE EMISSIONS DATA AND PROJECTIONS USED IN PLANNING

Most of the nationwide emissions data presented in Table II-1 and the projections in Figures II-1 through II-5 were supplied by the APCO Division of Air Quality and Emission Data (DAQED). DAQED is responsible for collecting and compiling the results of past and current nationwide emission inventories as well as projections of future emissions. Data are generated through efforts of DAQED, other APCO Divisions, and under APCO-sponsored contracts.

A basic tool for deriving emissions data is the list of emission factors in *Compilation of Air Pollution Emission Factors.*(1) These emission factors have been altered slightly by APCO in cases where additional information became available, such as emission-factor dependence on the age of an automobile. To derive emissions for past years, the emission factors can be applied to tabulations of fuel usage, vehicle miles, aircraft takeoffs and landings, etc., as published annually in the *Statistical Abstract of the United States.*(2) To forecast future emissions, these emission factors can be applied to projections of energy demand, fuel usage, and transportation activity. Projections are being developed continually by various Federal agencies such as the Federal Power Commission, the Bureau of Mines, and the Department of Transportation.

DEVELOPMENT OF EMISSION INVENTORY DATA IN TABLE II-1

The principal source of information for Table II-1 is *Nationwide Inventory of Air Pollutant Emissions, 1968.*(3) This book was prepared by DAQED as a tool for continuing improvement of the accuracy of nationwide emission inventories. It includes data for emissions for the year 1966 as well as 1968.

Many of the entries in Table II-1 were taken directly from the extensive unpublished source data of the DAQED compilations. In some cases in this study, emission source classes had to be subdivided. These subdivisions were made using references such as the *Census of Manufactures*(4) for guidance in calculating the amount of fuel used for combustion in various industries. Following is a discussion pointing out the differences between the breakdown of Table II-1 and the breakdown in Reference 3.

Combustible and Noncombustible Particulates

It was assumed that coal-fired power plants have boilers fired with pulverized coal and that 10 percent of the particulate emissions would be combustible particulate.(5) The emissions from internal-combustion engines and gas turbines were considered to consist almost entirely of combustible particulate, except for the lead portion. For other particulate-emissions sources, the combustible particulate was assumed to be 40 to 50 percent of the total, in agreement with various published data.

Industrial Combustion Sources

In Reference 3, the category "Industrial Processing" includes processing not involving combustion as well as processing involving combustion. The noncombustible emissions from the coke-production industry, the metals industry, and the chemical industry make up most of the difference between the "All Sources" and "All Combustion Sources" totals. In Table II-1 emissions from steam-generation equipment, process combustion equipment, and stationary gas engines are broken out specifically from the total for "Industrial Processing".

After reviewing published data(4) of fuel usage by industry classes, the Battelle team evolved a set of approximate percentages for the relationship of industrial steam-generation emissions to total industrial-combustion emissions.

The NAPCA research report by the Esso Research and Engineering Company(6) points out that the natural-gas engines used for pumping natural gas are an important source of NO_X. DAQED and DPCE have used the data in the Esso report for their nationwide emission inventories and emission projections.

To determine the emissions of other pollutants (chiefly CO and HC) from these natural-gas engines, the NO_X emissions reported by Esso and a set of emission factors suggested by Cooper-Bessemer(7) for two- and four-cycle engines were used. These factors are:

0.084 lb of NO_X/lb of fuel

0.01 lb of HC/lb of fuel

0.02 lb of CO/lb of fuel.

These emissions were placed in the "Stationary Gas Engines" category, and the remaining emissions from industrial combustion processing were placed under "Industrial Processing".

Thus the total industrial emissions for 1966 is equal to the sum of four emission sources as listed in Table II-1: (1) "Industrial Processing", (2) "Industrial Steam Generation – Coal, Oil, and Gas", (3) "Stationary Gas Engines", and (4) the difference between "Total, All Sources" and "Total, All Combustion Sources".

Aircraft

Aircraft emissions for 1967 have been inventoried by the Northern Research and Engineering Corporation.(8) This inventory was used to estimate the emissions for 1966 from both civilian and military aircraft during both cruise and terminal operations. The emissions were divided into those from jet aircraft and those from piston aircraft. The piston-aircraft emissions were added to the automobile and light-truck emissions. The sum appears in the "Mobile Gasoline Engine" column. Jet aircraft emissions are shown under "Gas Turbines".

Source Totals

The "All Sources" total figures, except those for CO and NO_x were taken directly from Reference 3. The CO and NO_x totals were modified because of some changes in data for industrial and mobile gasoline-engine emissions. The totals of emissions under "All Energy-Conversion Combustion" are the summation of all the entries in the table under the headings "Continuous Combustion" and "Cyclic Combustion". When the totals in the last two categories, "Solid Waste Incineration" and "Miscellaneous Combustion", are added to the totals under "All Energy Conversion Combustion", the "Total, All Combustion Sources" entries are obtained. "Miscellaneous Combustion" includes emissions from forest fires, structural fires in buildings, agricultural burning, coal-refuse burning, and wood burning. The differences between the "Total, All Sources" and "Total, All Combustion-Sources" are the emissions from non-combustion industrial processing and emissions attributed to vessels operating outside the United States.

SOURCES OF PROJECTIONS FOR COMBUSTION EMISSIONS

The curves in Figures II-1 through II-5 are a synopsis of the projections developed as an input for the rating scheme of research opportunities. In some cases, the curves represent a smoothing of the original data.

Tables B-1 through B-5 provide a tabulation of the data used in plotting the curves of Figures II-1 through II-5. These data were used to develop the values of the Projected Pollutant-Source Factors (S_{ij}).

In preparing these emission projections, a number of contributions were used: the energy-demand projections from Morrison and Readling(9), aircraft fuel usage and terminal-emission projections from the Northern Research report(8), NO_x-emission forecasts from the Esso report(6), automotive emission projections prepared by DAQED in 1969 and published in the *Nationwide Inventory of Air Pollutant Emissions, 1968*, and stationary-source emission projections prepared by DPCE in 1969-1970 based on projections of energy demand made by the Federal Power Commission and the Atomic Energy Commission.

The principal set of emission factors used has been those published by Duprey(1). Each of the emission-projection sources listed above involves a different variation of Duprey's factors. For industrial steam-generation emissions, the Battelle team used a set of factors based on other literature.

Because of the variety of data sources utilized for projecting future pollutant-emission levels, a few inconsistencies occurred between calculated projections and data reported in DAQED inventories, such as Reference 3, and tabulated in Table II-1. When these discrepancies occurred, the calculated projections were used in Tables B-1 through B-5. However, the discrepancies were not sufficiently large to effect the ranking of any R&D opportunities.

Table B-1 – Forecast of U.S. Pollutant Emissions From Combustion of Prime Fuels for Energy Conversion 1970, 10^6 tons/year

Pollutants	**Continuous Combustion for Energy Conversion**												**Cyclic Combustion for Energy Conversion**				
	Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. **Products of Incomplete Combustion**																	
Combustible Particulate	0.60	0.02	0.02	0.26	0.57	0.04	0.08	0.10	0.11	0.07	0.04	0.03	0.38	0.30	0.01	0.15	n
CO	0.08	n	n	0.02	0.12	0.01	<.01	0.43	0.03	<.01	0.04	0.29	55.0	0.20	1.7	0.10	0.50
HC	0.03	0.01	n	–	0.06	0.01	0.02	0.09	0.04	n	0.01	0.12	13.6	0.40	0.15	0.15	0.25
PNA[(a)]	n	n	n	0.30	n	n	n	6.3	0.10	0.10	n	n	0.48	n	n	n	n
2. **NO_x**	3.8	0.40	0.70	0.41	0.93	0.33	0.65	0.07	0.64	0.38	0.15	0.12	7.6	0.60	0.13	0.27	2.1
3. **Combustion-Improving Additives** Lead	n	n	n	n	n	n	n	n	n	n	n	n	0.23	n	<.01	n	n
4. **Fuel Contaminants**																	
SO_x	18.7	1.3	n	1.39	3.71	1.07	<.01	0.85	1.2	n	0.09	0.06	0.28	0.11	n	n	n
Ash	5.0	0.01	n	0.26	0.66	0.03	n	0.12	0.08	n	n	n	n	n	n	n	n

(a) PNA shown in 10^3 tons/year.

–, not available.

n, emission considered negligible.

Table B-2 – Forecast of U.S. Pollutant Emissions From Combustion of Prime Fuels for Energy Conversion 1975, 10^6 tons/year

Pollutants	Continuous Combustion for Energy Conversion												Cyclic Combustion for Energy Conversion				
	Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. Products of Incomplete Combustion																	
Combustible Particulate	0.60	0.02	0.02	0.29	0.53	0.05	0.09	0.07	0.12	0.08	0.03	0.03	0.45	0.35	0.02	0.15	n
CO	0.11	n	n	0.02	0.11	0.01	<.01	0.33	0.03	<.01	0.06	0.39	41.6	0.20	1.7	0.10	0.55
HC	0.04	0.01	n	–	0.06	0.01	0.02	0.07	0.04	n	0.02	0.17	8.3	0.50	0.14	0.14	0.27
PNA[(a)]	n	n	n	0.30	n	n	n	4.9	0.10	0.10	n	n	0.58	n	n	n	n
2. NO_x	4.8	0.55	0.85	0.46	0.88	0.39	0.75	0.05	0.68	0.46	0.37	0.25	9.7	0.80	0.13	0.27	2.3
3. Combustion-Improving Additives																	
Lead	n	n	n	n	n	n	n	n	n	n	n	n	0.27	n	<.01	n	n
4. Fuel Contaminants																	
SO_x	28.5	2.05	n	1.39	3.49	1.04	<.01	0.65	1.15	n	0.15	0.09	0.33	0.13	n	n	n
Ash	5.4	0.01	n	0.31	0.62	0.03	n	0.09	0.08	n	n	n	n	n	n	n	n

(a) PNA shown in 10^3 tons/year.

–, not available.

n, emission considered negligible.

Table B-3 – Forecast of U.S. Pollutant Emissions From Combustion of Prime Fuels for Energy Conversion 1980, 10^6 tons/year

Pollutants	Continuous Combustion for Energy Conversion												Cyclic Combustion for Energy Conversion				
	Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. Products of Incomplete Combustion																	
Combustible Particulate	0.60	0.02	0.02	0.27	0.55	0.05	0.10	0.06	0.13	0.10	0.05	0.04	0.54	0.41	0.02	0.20	n
CO	0.13	n	n	0.03	0.11	0.01	<.01	0.25	0.03	<.01	0.10	0.53	34.6	0.30	1.9	0.10	0.60
HC	0.05	0.01	n	–	0.06	0.01	0.02	0.05	0.04	n	0.04	0.23	5.8	0.60	0.19	0.19	0.30
PNA[(a)]	n	n	n	0.30	n	n	n	2.8	0.10	0.20	n	n	0.68	n	n	n	n
2. NO_x	5.7	0.70	1.0	0.60	0.91	0.43	0.85	0.04	0.73	0.56	0.59	0.37	11.9	1.0	0.17	0.33	2.5
3. Combustion-Improving Additives																	
Lead	n	n	n	n	n	n	n	n	n	n	n	n	0.34	n	<.01	n	n
4. Fuel Contaminants																	
SO_x	38.3	2.8	n	1.52	3.63	0.82	<.01	0.50	1.1	n	0.24	0.12	0.39	0.15	n	n	n
Ash	5.4	0.01	n	0.29	0.64	0.03	n	0.07	0.09	n	n	n	n	n	n	n	n

(a) PNA shown in 10^3 tons/year.

–, not available.

n, emission considered negligible.

Table B-4 – Forecast of U.S. Pollutant Emissions From Combustion of Prime Fuels for Energy Conversion 1990, 10^6 tons/year

Pollutants	Continuous Combustion for Energy Conversion												Cyclic Combustion for Energy Conversion				
	Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
	Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. Products of Incomplete Combustion																	
Combustible Particulate	0.50	0.03	0.03	0.26	0.55	0.06	0.12	0.03	0.15	0.15	0.14	0.09	0.62	0.48	0.03	0.25	n
CO	0.19	n	n	0.03	0.11	0.01	<.01	0.16	0.04	<.01	0.27	1.19	45.5	0.40	2.3	0.20	0.60
HC	0.07	0.01	n	–	0.06	0.01	0.03	0.03	0.05	n	0.10	0.52	7.3	1.0	0.25	0.25	0.30
PNA(a)	n	n	n	0.40	n	n	n	1.6	0.10	0.30	n	n	0.91	n	n	n	n
2. NO_x	9.0	1.0	1.6	1.07	0.91	0.50	1.03	0.02	0.83	0.85	1.5	0.83	17.1	1.5	0.20	0.40	2.5
3. Combustion-Improving Additives																	
Lead	n	n	n	n	n	n	n	n	n	n	n	n	0.46	n	<.01	n	n
4. Fuel Contaminants																	
SO_x	57.6	4.4	n	1.33	3.63	0.95	<.01	0.30	1.0	n	0.63	0.27	0.46	0.21	n	n	n
Ash	3.3	0.01	n	0.31	0.64	0.04	n	0.04	0.10	n	n	n	n	n	n	n	n

(a) PNA shown in 10^3 tons/year.

–, not available.

n, emission considered negligible.

Table B-5 – Forecast of Total 1970-1990 U.S. Pollutant Emissions From Combustion of Prime Fuels for Energy Conversion, 10^6 tons

Pollutants	Total, All Energy Conversion Combustion	Continuous Combustion for Energy Conversion													Cyclic Combustion for Energy Conversion				
		Central-Station Power Plants			Industrial Processing	Industrial Steam Generation			Commercial & Residential Space Heating			Gas Turbines		Mobile IC Engines		Stationary IC Engines		
		Coal	Oil	Gas		Coal	Oil	Gas	Coal	Oil	Gas	Stationary	Aircraft	Gasoline	Diesel	Gasoline	Diesel	Gas
1. **Products of Incomplete Combustion**																			
Combustible Particulate	60.7	11.5	0.5	0.5	5.4	10.9	1.0	2.0	1.2	2.6	2.1	1.3	0.9	10.7	5.8	0.4	3.9	n
CO	921.0	2.7	n	n	0.5	2.2	0.2	<.1	5.4	0.7	<.1	2.5	10.6	833.0	5.8	42.8	3.0	11.5
HC	192.5	1.0	0.2	n	–	1.2	0.2	0.5	1.1	0.9	n	0.9	4.9	155.3	13.0	3.8	3.8	5.7
PNA[a]	95.0	n	n	n	6.5	n	n	n	69.5	2.0	3.7	n	n	13.3	n	n	n	n
2. **NO_x**	580.7	121.3	12.6	21.5	13.2	18.1	8.5	16.9	0.8	14.6	11.7	12.8	8.5	242.0	20.5	3.3	6.5	48.0
3. **Combustion-Improving Additives**																			
Lead	6.8	n	n	n	n	n	n	n	n	n	n	n	n	6.8	n	<.1	n	n
4. **Fuel Contaminants**																			
SO_x	992.3	764.8	56.5	n	28.5	72.1	18.7	<.1	10.6	21.9	n	5.5	2.9	7.6	3.1	n	n	n
Ash	119.3	96.5	0.2	n	5.9	12.7	0.7	n	1.5	1.8	n	n	n	n	n	n	n	n

[a] PNA shown in 10^3 tons/year.

–, not available.

n, emission considered negligible.

The differences between the data presented in Figures II-1 through II-5 and the data in Tables B-1 through B-4 are as follows:

1. "Industrial Process" curves in the figures represent the summation of both "Industrial Steam Generation" and "Industrial Process" in the tables. This includes industrial steam generation by coal, oil, and gas.

2. "Commercial and Residential" curves in the figures represent the sum of commercial and residential space heating as listed under coal, oil, and gas in the tables.

3. No curves are presented in the figures for piston-engine aircraft.

4. In the figures the three curves for "Power-Total" labeled "No Controls", "Low Level of Controls", and "High Level of Controls" were obtained from Figure 6 of a paper by Hangebrauck and Spaite.(10) These data are not reported in the tables.

In both the tables and figures, nationwide emissions were considered; thus, aircraft emissions both at airports and during cruise were included in the totals for jet and piston aircraft. The basic data for aircraft emissions came from the Northern Research report(8). In that report, predictions of jet aircraft emissions included the expectation that smokeless engines would be installed between 1967 and 1979 which would reduce the quantities of particulate, CO, and HC emitted but increase the emission of NO_X. The Battelle forecasts do not include decreases in CO and HC emissions, as the technology for achieving these reductions has not yet been developed.

The following detailed discussion* of the development of the projections for combustion emissions is divided into two major parts: (1) Projections for Continuous-Combustion Applications and (2) Projections for Cyclic-Combustion Applications.

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*The following abbreviations are used in the explanatory notes.

M&R = Morrison and Readling(9)
Esso = Esso Research and Engineering Company(6)
C-B = Cooper-Bessemer(7)
NR = Northern Research and Engineering(8)
HLM = Hangebrauck, von Lehmden, Meeker(11)
DOT = Department of Transportation.

PROJECTIONS FOR CONTINUOUS-COMBUSTION APPLICATIONS

Total Particulates*

- Power Plants; Coal

  These are unpublished DPCE projections based on the Federal Power Commission's unpublished estimates of power requirements and the assumption of an increased percentage of both existing and new coal-fired power plants being equipped with particulate controls.

- Power Plants; Oil and Gas

  Battelle made this projection on the basis of the M&R fuel-usage projections. No increase in controls was assumed and the same emission factors as used by NAPCA for establishing 1966 emissions were used.

- Industrial Steam Generation

  The M&R forecast of energy requirements** to 1980 was used and extended to 1990 at the same rate of growth. The following emission factors representing information in several publications were used:

Total Particulate

Emissions, lb/10^6 Btu		
Coal	Oil	Gas
0.26	0.11	0.024

  It was further assumed that 60 percent of the particulate emissions from coal combustion were removed by control devices.

- Industrial Processing

  This value is the difference between the total emissions from industrial combustion and the steam-generation portion of those emissions. The forecasts of total industrial emissions of particulates from coal combustion were obtained from DPCE for 1970 (a value of 1.72 x 10^6 tons). The gas contribution was considered as negligible and the fuel-oil contribution was taken as 10 percent of the coal sum. It was assumed that the coal usage would remain constant through 1990, while the fuel-oil emissions would increase at the rate of fuel-oil-usage increase predicted by M&R.

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*The projection of total particulate emission from all sources was made prior to breaking down the particulates into combustibles and noncombustibles (or ash). Only total particulates are considered.

**There seems to be a contradiction between the M&R forecast for industrial energy requirements and their forecast for the coal, oil, and gas requirements through 1980. All of these curves are relatively constant except the curve for the coal tonnage requirements which drops sharply. The M&R projection for energy demand was used instead of their coal tonnage forecast to develop industrial emissions.

- Commercial and Residential

The 1966 value of emissions was broken down into coal, oil, and gas emissions following ratios developed by Battelle. The M&R rates of growth of commercial and residential fuel usage from 1965 to 1980 were plotted and extrapolated to 1990. Particulate emissions from coal, oil, and gas combustion were projected from 1966 to 1990 following the fuel projections.

- Aircraft Gas Turbines

The NR report gives a 1967 value for fuel consumption by civilian and military jets and emission indices for cruise with the note that 80 percent of the fuel is consumed during cruise. From this, 1967 emissions during cruise were determined. After 1979, the civilian-aircraft emissions in terminals were predicted to increase at a 10 percent growth rate. It was predicted that civilian traffic will increase at a 10 percent growth rate through 1990, a growth rate similar to the growth rate shown in the civil aviation portion of NR's Figure 10.

The military-aircraft cruise activity was held constant at the 1967 level. The 1967 military-aircraft emissions in terminals were taken to be in the same ratio to civilian-aircraft emissions in terminals as the military- and civilian-aircraft emissions during cruise. Military-aircraft emissions in terminals were taken as constant from 1967 to 1990.

The NR report takes into account a drop of 50 percent in particulate emissions in terminals between 1967 and 1979, owing to the installation of smokeless engines. Projections for military aircraft emissions in terminals were reduced by the Battelle team by this same factor over the same time period. For emissions of particulate during cruise, a 50 percent drop starting in 1975 was assumed.

The sum of all military- and civilian-aircraft emissions during cruise and in terminals is given in Tables B-1 through B-4.

- Stationary Gas Turbines

Estimates were made of the 1969 emissions of pollutants from stationary gas turbines on the basis of the fact that the fuel consumption of stationary turbines in 1969 was equal to the 1967 fuel consumption by aircraft turbines. Emissions of the different pollutants were derived from judgments of the relation between aircraft cruise emissions and the emissions from stationary turbines which would generally be running in the same mode.

The ratios of the nationwide emissions from aircraft gas turbines (total of military and civilian aircraft, terminal, and cruise) to industrial and utilities gas turbines, if both aircraft and stationary gas turbines used the same amount of fuel, were estimated as follows:

Pollutant	Ratio of Aircraft Gas Turbine Emissions to Stationary Gas Turbine Emissions
Combustible particulate	1 to 1
CO	10 to 1
HC	10 to 1
NO_x	1 to 1
SO_x	0.5 to 1

A growth rate of 16 percent for stationary gas turbine purchases in recent years was reduced to 10 percent by Battelle in predicting 1970-1990 emissions. The emission forecasts were projected from the 1969 figures and, as was done for aircraft, the particulate emissions were cut in half after 1975.

Carbon Monoxide

- Power Plants

  Using M&R fuel-usage forecasts, DAQED projected emissions for 1970 and 1975. These data were developed by DAQED in early 1969 using Duprey's emission factors (to the Battelle team's knowledge, the projections are unpublished). The forecasts were extended to 1980 using M&R fuel-usage forecasts and to 1990 using an extrapolation of the M&R forecasts.

- Industrial Steam Generation

  See procedure for particulates, page B-10, except:
  - no control of emissions assumed
  - emission factors used are as follows:

CO Emissions, lb/10^6 Btu		
Coal	Oil	Gas
0.10	0.013	0.0004

- Industrial Processing

These CO emissions were taken to be the difference between total industrial emissions and total industrial steam-generation emissions. DAQED made forecasts of 1970 industrial-processing emissions from the combustion of coal, oil, and gas. These were projected to 1980 by the Battelle team following the M&R projection of energy demands by industry for the three fuels and to 1990 by extrapolating the M&R curves.

- Commercial and Residential

See procedure for projecting particulates, page B-11.

- Aircraft Gas Turbines

The same procedure was followed as for particulates from this source except that no reduction in emissions during cruise was assumed in 1975 after the completion of smokeless engine installations, and the emissions in terminals were assumed to increase from 1967 to 1990 at a 10-percent growth rate, instead of using the 1979 value given in Table 55 of the NR report.

- Stationary Gas Turbines

See procedure for projecting particulates, page B-11, except:
  - no reduction assumed after 1975 engine changeovers.

Hydrocarbons

- Power Plants

See procedure for CO, page B-12.

- Industrial Steam Generation

See procedure for CO, page B-12.
  - emission factors used are as follows:

HC Emissions, lb/10^6 Btu		
Coal	Oil	Gas
0.054	0.017	0.005

- Industrial Processing

  See procedure for CO, page B-13.

- Commercial and Residential

  See procedure for particulates, page B-11.

- Gas Turbines, Aircraft and Stationary

  See procedure for CO, page B-13.

Polynuclear Aromatics (PNA)

- Power Plants

  Using the 1965 PNA emissions calculated by DAQED and the fuel usage in 1966 interpolated from the M&R report, a base emission factor was established. The emissions were projected to 1990 following the M&R fuel projections and the Battelle extrapolation of them. DAQED had broken down emissions from coal and fuel-oil stationary combustion into power plant, industry, and residential. The Battelle team apportioned the 1966 total of emissions from natural-gas combustion (234 tons) into the following distribution:

PNA Emissions From Stationary Sources Fired by Natural Gas

	Tons/year
Power Plants	0
Industrial Combustion	134
Residential & Commercial	100

These divisions were made after consulting HLM (pp 11 and 14), assuming that emission factors would be about the same from both industrial and residential sources if the combustion air/fuel ratios were correctly adjusted. The emissions of 134 tons and 100 tons then reflect the ratio of natural gas used by these sources.

- Industrial Steam Generation and Processing

  Using the DAQED and the Battelle apportioning of 1966 PNA emissions (see previous paragraph), future emissions were projected following the M&R forecasts of industrial energy demand. It was assumed that 90 percent of the total industrial combustion emissions of PNA were from processing and 10 percent were from steam generation.

- Commercial and Residential Heating

  As described in the previous two paragraphs, future PNA emissions were projected to follow the 1980 M&R fuel-usage forecasts and the Battelle extensions of these fuel forecasts to 1990.

- Gas Turbines

  In the absence of any data, emissions from these sources were considered to be negligible.

Nitrogen Oxides

The best reference for projections of NO_x is the Esso report (Table 3-34). Before this was available, earlier data were provided to Battelle by DAQED, but these are in substantial agreement with Esso forecasts.

- Power Plants

  See procedure for CO, page B-12.

- Industrial Steam Generation and Processing

  See procedure for CO, page B-12, B-13.
  – emission factors used are as follows:

NO_x Emissions, lb/10^6 Btu		
Coal	Oil	Gas
0.79	0.58	0.20

- Commercial and Residential Heating and Gas Turbines

  See procedure for particulates, page B-11.

Sulfur Oxides

- Power Plants

DPCE has projected emissions from power plants on the basis of a forecast (unpublished) of power demands made by the Federal Power Commission. These total utility emissions were divided between coal, fuel oil, and gas in the same ratio as the 1966. SO_x emissions listed in Table II-1. No SO_x controls were assumed in these projections.

- Industrial Steam Generation

See procedure for CO, page B-12.
– emission factors used are as follows:

SO_x Emissions, lb/10^6 Btu		
Coal	Oil	Gas
3.15	1.87	0.0008

The SO_x emissions from oil-fired steam generation were altered to correspond to a drop in the sulfur content of the oil from 1.7 percent to 1 percent between 1970 and 1980.

- Industrial Processing

This is the difference between total emissions from industrial combustion and emissions from industrial steam generation. The total emissions from industrial combustion are the sum of a DPCE forecast of SO_x emissions from the burning of distillate and residual oil by industry, a Battelle forecast of coal emissions, and an estimate of emissions from burning natural gas which were considered to be less than 0.01 x 10^6 tons per year.

The projection of total industrial coal-combustion emissions of SO_x was made by estimating 1965 emissions using the M&R values of coal burned by industry, 9.87 x 10^7 tons, and the emission factor of 38 S from Table 3 of the Duprey report; S is assumed to be 2.6 percent sulfur. This estimate of 1965 emission was projected to 1990 following the M&R projections of 1980 industrial energy demands from coal and was extrapolated to 1990.

- Aircraft Gas Turbines

On page 3 of the NR report, a value of SO_2 emissions at FAA-controlled terminals is given for 1967. Military-aircraft emissions in terminals were approximated as being equal to the civilian-aircraft emissions following the almost equal amounts of fuel consumed by these jets in 1967 (Table 49 of the NR report). Since 80 percent of the fuel is consumed in the cruise mode, the cruise emissions of SO_2 were determined by multiplying the terminal emissions by 4.

Starting with these 1967 base emissions, civilian-aircraft emissions in terminals and during cruise were projected to increase to 1990 at a 10-percent growth rate, while military-aircraft emissions were projected to remain at their 1967 level. The sums of civilian- and military-aircraft emissions are entered in Tables B-1 through B-4.

- Stationary Gas Turbines

A 1969 value of SO_x emissions was determined as described in the preceding write-up on particulate emissions from stationary gas turbines. This emission was then projected to grow at a 10 percent rate until 1990.

PROJECTIONS FOR CYCLIC-COMBUSTION APPLICATIONS – IC ENGINES

All Pollutants

- Mobile Gasoline Engines

These emissions are the sum of the emissions from gasoline-powered motor vehicles and from piston-engine aircraft. DAQED furnished Battelle a DOT projection to 1990 of motor-vehicle-miles per year. This projection is divided into automobiles, light-duty trucks, and several classes of heavy-duty trucks. It is assumed that the automobiles and light-duty trucks use gasoline, while the heavy-duty trucks use diesel fuel.

Using the DOT projections, DAQED made forecasts of the emissions of CO, HC, and NO_x with the assumption of the implementation of 1970 standards for the control of automobile emissions (CO and HC). This forecast was made in 1969 with the additional assumption that the test-cycle procedures would not be changed. The projections have been published in *Nationwide Inventory of Air Pollutant Emissions, 1968*(3).

For the projections of motor-vehicle emissions of total particulate (consisting almost entirely of combustible particulate) and of SO_x, the DOT vehicle-mile forecasts and the Duprey emission factors were used. The DOT projections were also used in making the forecasts of PNA and lead emissions. These two pollutants were predicted to increase from their base values at the same growth rate as vehicle miles. These base values were given by DAQED as 215,000 tons of lead emitted from automobiles in 1967, 304 tons of PNA emitted from automobiles in 1966, and 136 tons of PNA emitted from trucks in 1966.

The piston-engine-aircraft emission projections were obtained from the NR report using the table on page 3 of that report as a base for calculating 1967 civilian-aircraft emissions at terminals. Then 1967 military- and civilian-aircraft emissions during cruise were obtained using 80 percent of the fuel listed in NR Table 49 and using the emission factors in that table. The military-aircraft emissions in terminals for 1967 were assumed to have the same ratio to civilian-aircraft emissions in terminals as the ratio of military- to civilian-aircraft fuel used in 1967.

The emissions were projected to follow the curves in NR Figure 10 which gives the piston-engine fuel consumption to 1979 for civil aviation and total aviation. Military-aircraft consumption was taken as the difference between total and civil aviation. Beyond 1979, civilian-aircraft emissions were forecast to increase at a growth rate of 3 percent, while military-aircraft emissions would remain constant at the 1979 level.

- Mobile Diesel Engines

Emissions of PNA and lead from piston-engine aircraft were considered to be negligible. The emissions of all pollutants from diesel-powered vehicles were projected to increase from the 1966 values at the rate of growth predicted by DOT for the total of all classes of heavy-duty trucks. Data on emissions from railroad diesel engines were not available at the time the projections were made and were not included in this category. Inclusion of these data would increase mobile diesel engine emission totals but would not have affected ranking of R&D opportunities.

- Stationary Gasoline and Diesel Engines

In 1969 DAQED made projections of CO, HC, and NO_X to 1990 for nonhighway use of motor fuels. The predicted emissions of each of these pollutants were divided between diesel and gasoline in the same ratios as were true in 1966.

The combustible particulate emissions from stationary diesel and gasoline engines were predicted to increase at the same rate as DAQED had predicted for HC emissions from these sources. SO_X emissions were considered to be negligible.

- Stationary Natural-Gas Engines

The Esso report points out the importance of NO_X emissions from the natural-gas-powered pumps used for pipelines and gas plants. This report gives forecasts to 2000 for the NO_X emissions from these gas engines. Using the C-B set of emission factors for two- and four-cylinder engines, estimates were made of the emissions of HC and CO. These emissions were predicted to increase at the same rate as the Esso forecast for NO_X emission from these engines.

Emissions of pollutants other than NO_X, CO, and HC from stationary gas engines were considered to be negligible.

REFERENCES FOR APPENDIX B

(1) Duprey, R. L., *Compilation of Air Pollutant Emission Factors*, Second Printing, USDHEW Public Health Service Publication No. AP-42, Raleigh, North Carolina (1968), 67 pp.

(2) U.S. Bureau of the Census, *Statistical Abstract of the United States*, U.S. Government Printing Office, Washington, D.C. (1967).

(3) *Nationwide Inventory of Air Pollutant Emissions, 1968*, USDHEW Public Health Service Publication No. AP-73, Raleigh, North Carolina (1970), 36 pp.

(4) U.S. Bureau of the Census, *Census of Manufacturers: 1963, Fuels and Electric Energy Consumed in Manufacturing Industries: 1962*, Series M63(1)-6, U.S. Government Printing Office, Washington, D.C. (1964).

(5) Smith, W. S., and Gruber, C. W., *Atmospheric Emissions From Coal Combustion – An Inventory Guide*, USDHEW Public Health Service Publication No. AP-24, Cincinnati, Ohio (1966), pp 63-65.

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(7) Personal communication in July, 1970, between F. Creswick of Battelle Memorial Institute, Columbus Laboratories, and M. Helmick of The Cooper-Bessemer Division of Cooper Industries.

(8) Final Report to National Air Pollution Control Administration, "Nature and Control of Aircraft Engine Exhaust Emissions", from Northern Research and Engineering Corporation (November, 1968), 388 pp, Contract No. PH 22-68-27.

(9) Morrison, W. E., and Readling, C. L., *An Energy Model for the United States Featuring Energy Balances for the Years 1947 to 1965 and Projections and Forecasts to the Years 1980 and 2000*, Bureau of Mines Information Circular IC 8384 (July, 1968).

(10) Hangebrauck, R. P., and Spaite, P. W., "Pollution From Power Production", paper presented at 25th Annual Convention of the National Limestone Institute, Washington, D.C. (January, 1970).

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